Experimental Evaluation of CAM and DENM Messaging Services in Vehicular Communications

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Abstract

The Cooperative Awareness Basic Service and Decentralized Environmental Notification Basic Service have been standardized by the *European Telecommunications Standards Institute* (ETSI) to support vehicular safety and traffic efficiency applications needing continuous status information about surrounding vehicles and asynchronous notification of events, respectively. These standard specifications detail not only the packet formats for both the *Cooperative Awareness Message* (CAM) and *Decentralized Environmental Notification Message* (DENM), but also the general message dissemination rules. These basic services, also known as *facilities*, have been developed as part of a set of standards in which both ISO and ETSI describe the Reference Communication Architecture for future *Intelligent Transportation Systems* (ITS). By using a communications stack that instantiates this reference architecture, this paper puts in practice the usage of both facilities in a real vehicular scenario. This research work details implementation decisions and evaluates the performance of CAM and DENM facilities through a experimental testbed deployed in a semi-urban environment that uses IEEE 802.11p (ETSI G5-compliant), which is a WiFi-like communication technology conceived for vehicular communications. On the one hand, this validation considers the development of two ITS applications using CAM and DENM functionalities for tracking vehicles and disseminating traffic incidences. In this case, CAM and DENM have demonstrated to be able to offer all the necessary functionality for the study case. On the other hand, both facilities have been also validated in a extensive testing campaign in order to analyze the influence in CAM and DENM performance of aspects such as vehicle speed, signal quality or message dissemination rules. In these tests, the line of sight, equipment installation point and hardware capabilities, have been found as key variables in the network performance, while the vehicle speed has implied a slight impact.

Keywords:
CAM, DENM, experimental evaluation, V2I, vehicular networks, intelligent transportation systems

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1. Introduction

Cooperative applications in vehicular scenarios are becoming essential for the future connected vehicle within the ITS (Intelligent Transportation Systems) research field. They are supposed to decrease road fatalities, improve the capacity of roads, diminish the carbon footprint of road transport and enhance the user experience during travels. Although there are many vehicular applications envisioned for the short, medium and long term, these can be categorized in the next groups (Khaled et al., 2009; European Telecommunications Standards Institute, 2009b):

- *Safety*. These kind of applications are intended to reduce accidents and safeguard vehicle occupants and pedestrians lives. Some examples are collision avoidance, accident notification or emergency vehicle approaching.
- *Traffic efficiency*. In this group there are applications that improve the road network capacity and reduce the travel time. Some examples are variable speed limit, dynamic management of road intersections or congestion detection and mitigation.
- *Infotainment*. Mainly oriented to provide value-added comfort applications, Internet access and multimedia. Some examples are context-aware touristic guidance, video on demand and video conferencing.

Although many of these applications have hitherto been proposed together with specific protocols designed from scratch, researches have recognized this is not a scalable way of supporting multiple services within the same information system. With the exception of some services, such as multimedia or common Web access, many ITS applications require a communication strategy that falls within one of the next two groups (or both of them):

- **Periodic status exchange**. Messages needed by applications to know about the status of vehicle or roadside terminals. These exchanges are usually data packets periodically sent by a terminal that contain information about location, speed or terminal identifier, among others.
- **Asynchronous notifications**. This kind of messages are used to inform about a specific event. In contrast to the previous status messages, the reliable delivery of these messages to a single terminal or a group of them is usually a key requirement due to the importance of the information carried.

Examples of the usage of the first messaging type can be found on traffic efficiency applications such as remote vehicle monitoring, which gathers periodic status data from vehicles, or safety applications such as cooperative collision avoidance, which requires kinematic information about surrounding vehicles to detect potential impacts. Asynchronous notifications are mainly found in safety applications, such as slippery pavement or post-collision warning.

Due to the proliferation of numerous ITS applications requiring the usage of these two communication strategies, according to the ISO/ETSI reference ITS communication architecture (Kosch et al., 2009; European Telecommunications Standards Institute, 2010a; International Organization for Standardization, 2013), ETSI has defined two basic messaging services (also known as *facilities*) included in the communications stack as a common reusable middleware. These are the Cooperative Awareness Basic Service (European Telecommunications Standards Institute, 2011), defining the *Cooperative Awareness Message* (CAM), and the Decentralized

Environmental Notification Basic Service (European Telecommunications Standards Institute, 2010b), which specifies the *Decentralized Environmental Notification Message* (DENM).

The ISO/ETSI reference ITS communication architecture considers Personal, Vehicle, Roadside and Central ITS Stations communicating by means of an ITS network to provide cooperative services. In this frame, CAM messages are exchanged among them to notify their presence, position and status in a single hop distance through a wireless channel, which is understood to be a wireless communication link based on the IEEE 802.11p technology and following the ETSI G5 specifications. On the contrary, DENM messages can be transmitted in a multi-hop way to cover a concrete geographic dissemination area. Both the format and the conditions under which CAM and DENM messages are generated are also specified by their corresponding international standards, although there are implementation decisions that are left for the developer.

CAM and DENM implementations on vehicular communications stacks are limited, and their support on commercial products is almost nonexistent so far. Due to this, its evaluation on real vehicular environments using the communication technologies conceived for the transmission of these messages is a pending issue in the literature. In this paper, a reference communications stack that follows the ETSI/ISO reference ITS communication architecture is used as the basis for integrating both CAM and DENM messaging facilities. This prototype implementation has been used to validate these basic services in two ways. On the one hand, in order to verify the capabilities of CAM and DENM, two real ITS applications have been developed for tracking vehicles and disseminating traffic incidences. On the other hand, a real semi-urban testbed has been deployed for validating these facilities and assessing the performance considering factors such as vehicle speed, signal quality, message dissemination rules, etc.

While the CAM and DENM packet structure is completely standardized, the message generation algorithms are only briefly described textually by ETSI. In this paper, reference algorithms compliant with available specifications are presented in detail. Apart from the great experimental effort to also validate ITS application services in real driving environments, the following novel ontributions are presented and tested:

1. CAM and DENM messages are transmitted using IPv6 multicast over 802.11p/ETSI G5.
2. The Roadside ITS Station forwards CAM messages from the Vehicle ITS Station to the Central ITS Station, and forwards DENM messages in the opposite direction.
3. The Central ITS Station includes a facility to distribute DENM messages among Roadside ITS Stations within the target area of the event to be reported.
4. The reference applications developed can also serve other third-party applications on the Internet through Web service interfaces.
5. The Vehicle ITS Station Mobile Router entity generates CAM messages, while it only forwards DENM messages received from outside to the in-vehicle network, where the Vehicle ITS Station Host is connected with. Since the last one executes final user applications, it is also in charge of decoding DENM messages.

The paper is organized as follows. First, Section 2 overviews CAM and DENM in order to prepare the reader for the rest of the document. Section 3 places the work in the research literature. Next, Section 4 presents the reference communication architecture and the new modules included to support CAM and DENM messaging. After that, the development of these new modules is described in detail in Section 5. Section 6 describes the two applications developed to validate the capabilities claimed by the standard specifications. In Section 7 it is presented an experimental evaluation to analyze the messaging operation and the communication network performance. Finally, the paper is concluded in Section 8.

2. Background

In the following we provide an overview of the CAM and DENM messaging facilities, which are the messaging services standardized within ETSI. Knowing the basic operation of these facilities is necessary for a correct understanding of the contributions presented in this paper.

2.1. CAM: Cooperative Awareness Basic Service

CAM (European Telecommunications Standards Institute, 2011) provide a basic awareness service in cooperative ITS networks, by means of periodic sending of status data to neighbouring nodes. This service can be viewed as an application support facility in charge of periodically distributing messages containing information of presence and location, as well as basic status. CAM messages are disseminated to neighbouring ITS stations that are located within a single hop distance from the sender. By receiving CAM messages, the ITS station is aware of other stations in its neighbourhood area as well as their positions, movement and relevant characteristics.

The receiver of a CAM message is expected to evaluate the relevance of the information contained within the message. This allows ITS stations to get information about its surroundings and act accordingly. Depending on the ITS station type, this ETSI standard defines a set of information that may be included within a CAM message and that can be of general interest for ITS applications operating on top of CAM facilities (e.g approaching emergency vehicle or slow vehicle warning). Anyway, the standard is flexible enough and allows the definition of new pieces of information, in order to meet the objective of transporting information relevant for ITS applications.

According to the ETSI TS 102 637-2 standard, the CAM message format is integrated by a header and a body. The header collects information about the message, such as version, message identifier and generation time. The body contains information about the ITS station sending the message:

- Identifier that univocally identifies the sending ITS station.
- Type of ITS station (mobile, public authority, private, etc.).
- Reference position expressed as latitude, longitude, elevation and heading.
- A set of accompanying CAM parameters, that can be optionally included following the recommendations made by the standard according to the ITS station type.

Apart from the CAM message format specification, the ETSI standard indicates the message handling processes to be carried out. On the one hand, the document provides guidance about the timing requirements for the periodic generation of CAM messages. According to the type of ITS application using CAM messaging facilities, the frequency can be adjusted to achieve a better operation. On the other, the standard specification also describes generation rules that help to determine when a CAM message must be sent. Nevertheless, as stated by the standard, these are general rules and several decisions are left to the architects employing CAM facilities.

2.2. DENM: Decentralized Environmental Notification Message

DENM (European Telecommunications Standards Institute, 2011) constitutes another type of application support facility providing a notification service about road status. Despite this type of facility has been specially conceived by ETSI to support active road safety applications, its application can be extended to any ITS application interested in obtaining information about road traffic conditions.

A DENM transmission is triggered by a certain ITS application that detects a relevant driving environment or traffic event. The application solicits to the DENM messaging facility the transmission of DENM messages notifying about the event. According to the standard specification, an event is characterized by an *event type*, which is an identifier associated to the type of event detected (e.g. vehicle breakdown, traffic jam, etc.); an *event position* describing either a concrete position or geographical area; the event *detection time*, which is an expiration time representing when the event is expected to be terminated; a *destination area* indicating the geographical area over which the DENM message needs to be disseminated among ITS stations; and a *transmission frequency* of the DENM messages issued by the same ITS station.

This information must be provided by the ITS application to the DENM facility, which will be in charge of periodically transmitting DENM messages over the specified destination area according to the indicated frequency. When the status of the event changes, the ITS application informs the DENM facility to modify the information contained within the DENM message. Once the expiration time is reached, the DENM facility stops sending DENM messages. Alternatively, events can be explicitly canceled by sending DENM messages informing about this situation.

The ITS station receiving a DENM message must determine the relevance of the information contained in the message and determine the actions to be taken (e.g. notify the driver). Additionally, the receiving station probably may forward the message to neighbouring ITS stations, either vehicle or roadside. This process is necessary to disseminate the message through the destination area indicated by the ITS station that originated the event. Therefore, compared to CAM messages, DENMs are disseminated to a longer distance, i.e., can be forwarded several hops away from the sending ITS station. A special situation happens with roadside ITS stations, which are expected to collect the broadcasted information from vehicle ITS stations, process the information and forward the information to a central ITS station. This aggregated information represents a valuable input for the road operator to improve both the traffic efficiency and traffic management. As observed, in this case, DENM messages are disseminated through V2V/V2I communication patterns.

The ETSI TS 102 637-2 standard defines that a DENM message is composed by a header (similar to the one used in the CAM message) and a body containing event information. This event information is organized into three categories:

- Management: includes general information about the event. A pair of station identifier and message number for the univocal identification of the event source, a version of the event, the expiration time, the sending frequency, the probability (*reliability*) of the event to be true, and an additional field that indicates if the event is false.

- Situation: includes specific details about the event informed in the message. The fields chosen are the situation cause and sub-cause, which detail the class of the event notified according to a predefined list in the standard, and the severity, which warns about the danger level using a set of four possible values ("informative", "obstacles", "danger", "highest danger").

- Location: includes the event location data. The event position part includes the coordinates of the hazard in the same format as in the CAM message, and extra trace location data, which defines an itinerary approaching to the event position.

In addition to the message format specification and data elements, the ETSI standard provides guidance about DENM handling processes. For example, a set of rules are identified in order to correctly forward DENM messages, to detect outdated DENM messages or to control those cases where the same event is being notified by multiple originator ITS stations. Unfortunately, the standard leaves some relevant aspects undefined. For example, despite the standard acknowledges the importance of the communication path between the central and roadside ITS stations to transmit DENM information, there is no description about how this process must be implemented.

3. State of the Art

Despite CAM and DENM constitute the basic set of messages established by the standardization forum to assist the operation of cooperative ITS applications, it is difficult to find research works contemplating the usage of these messaging capabilities. For example, Aguilera Leal et al. (2010) develop a new geographic routing protocol for disseminating information in vehicular adhoc networks (V2V communication) that is optimized by using the information available in the CAM messages periodically broadcasted by vehicles. Similarly, the information contained by CAM and DENM messages is taken as reference by Menouar et al. (2011) to define an information model for the local dynamic map, which stores information collected by vehicles such as traffic incidents in the surroundings, point of interest (restaurants or gas stations), etc. Another work acknowledging the importance of CAM/DENM messages for enabling road safety applications can be found in Araniti et al. (2013). This work analyzes the possibility of establishing an ITS communication infrastructure where CAM and DENM messages are transmitted using the LTE cellular technology. Another related work (Sepulcre et al., 2013) develops a testing platform intended to evaluate the effectiveness of relevant vehicular safety applications which are implemented using the capabilities offered by CAM and DENM messages. Finally, the CAM/DENM message format also guides the work conducted by Nair et al. (2013), where it is developed a routing protocol for vehicular networks specially concerned with reducing the bandwidth usage by applying data aggregation to avoid redundant information transmission.

The development of ITS applications able of either tracking the position of vehicles or notifying road incidents in a specific geographical area, has been an issue extensively investigated. Regarding the former, we find numerous solutions (Lu et al., 2009; Sivaraman and Trivedi, 2010; Vu et al., 2010) proposing a vehicle tracking system based on video cameras deployed along the road. Alternatively, other solutions (Menard et al., 2011; Menard and Miller, 2011) propose vehicle tracking systems based on the GPS location capabilities integrated by the driver's smartphone. Finally, there exists another group of solutions suggesting the implementation of tracking services using alternative mechanisms based, for example, on sensor networks (Aravind et al., 2009) or RFID technology (Anuradha and Sendhilkumar, 2011). Unfortunately, none of these works take advantage of the CAM communication capabilities, which considerably reduce the necessary economic investment to implement the tracking service. With respect to the road incidents applications, in the literature we can also find a wide number of works (Fogue et al., 2012; Liu and Chigan, 2012; Liu and Lee, 2012; Ruiz et al., 2012; Ghandour et al., 2013). However, these solutions do not contemplate the usage of the standardized DENM facility. Furthermore, all these approaches are restrictive in that they do not allow the infrastructure to generate events that need to be disseminated in a certain road segment. The road incidences application we present in this paper overcomes all these drawbacks.

Finally, another noticeable contribution of this work relies on the development of an experimental validation of the vehicle tracking and dissemination applications over a real vehicular network and using the IEEE 802.11p technology, which is especially adapted to the conditions arisen in vehicular communications. To the best of our knowledge, there exists a few works dealing with the evaluation of 802.11p-based communications at network level, especially within our research line (Santa et al., 2014). However, prior evaluations are focused on IPv6 network mobility and only include a small reference set of tests. Moreover, some works have recently appeared evaluating the behavior of 802.11p-based networks at link level. The evaluations performed by Shagdar et al. (2012) reveal that the packet delivery ratio achieved by the technology is highly dependent on the distance between sender and receiver. These results are confirmed by Lin et al. (2012), where it is also concluded that the vehicle speed does not imply a noticeable performance degradation of the communication. A similar evaluation is performed by Gozalvez et al. (2012), but this time carrying out a great testing campaign in a city.

Part of the evaluation conducted in this work also consists in the assessment of the signal quality in a real semi-urban testbed using IEEE 802.11p, which is a necessary step prior to the performance analysis of the ITS communication architecture presented in this paper. In this study, we confirm the conclusions reached by previous works in this field. On the one hand, the existence of a valid 802.11p connectivity is conditioned to the existence of a direct line of sight between the sender and receiver. Unlike previous works, we have also detected that the signal quality depends on the relative altitude between the sender and the receiver and the capabilities of the specific hardware used for wireless transmission and reception. Finally, another noteworthy conclusion of this work is that the vehicle speed has a slight influence in the transmission of information through the 802.11p wireless link, however, our experimentation has revealed that the lowest packet delivery ratios are achieved at high speeds.

4. System Architecture

The base vehicular architecture used in this paper for developing the CAM and DENM functionalities was initially presented in Santa et al. (2014). This section summarizes the reference architecture and the communication stacks of the different entities, and presents the new modules integrated in the framework for supporting the messaging facilities.

4.1. Base Communication Architecture Overview

Fig. 1 shows a simplified view of the communication architecture presented in Santa et al. (2014), which follows the ISO/ETSI reference architecture specifications (European Telecommunications Standards Institute, 2010a; International Organization for Standardization, 2013). In the diagram one can distinguish three main entities: Vehicle ITS Station (Vehicle ITS-S), integrating the on-board networked nodes for accessing the whole network; Roadside ITS Station (Roadside ITS-S), which provides local wireless connectivity and data processing; and Central ITS-S (Central ITS-S), which includes the necessary nodes for providing infrastructure services. The communication stacks depicted for each node follow the ISO/ETSI six-layer scheme with: access technologies, networking and transport, facilities, applications, management and security.

In the vehicle the stack functionality is split into two nodes: vehicle ITS-S host and vehicle ITS-S router (also known as Mobile Router - MR). The MR includes the needed functionalities to hide networking tasks to in-vehicle hosts. An unlimited number of hosts could connect to the ITS network by means of the MR through a common wireless connection (e.g. IEEE 802.11a/b/g) or

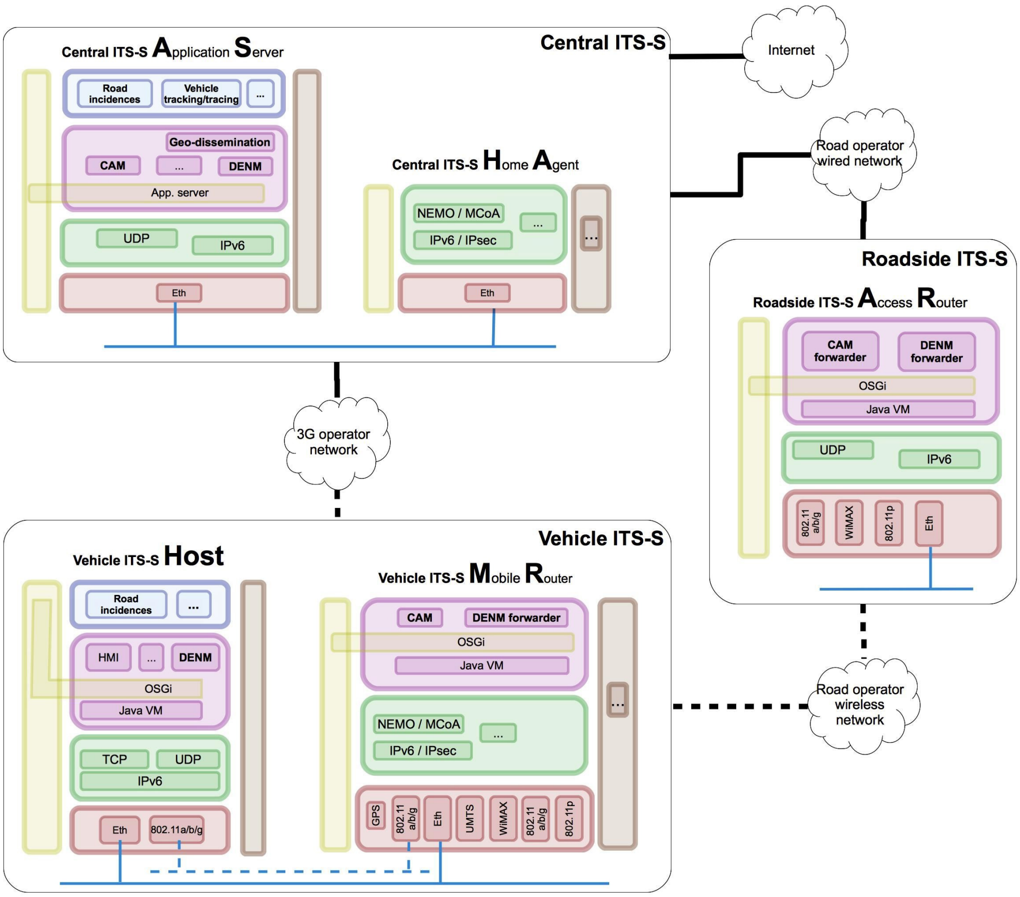


Figure 1: Overall architecture of the reference vehicular network

an Ethernet link. To maintain external communication with roadside equipment and the control centre, the following communication technologies are integrated: 3G/UMTS, WiMAX, WiFi and 802.11p (ETSI G5-compliant). A GPS device in the lower layer enables the vehicle to be geo-located.

IPv6 connectivity is supported by the set of elements included within the networking and transport layer of the MR. On one hand, Network Mobility (NEMO) (Devarapalli et al., 2005) is in charge of maintaining reachability for the whole in-vehicle IPv6 network. Additionally, to support the multihomed configuration of the mobile router, the NEMO operation is assisted with MCoA (Wakikawa et al., 2009). Regarding security, the mobile router is equipped with the needed elements to secure mobility-related traffic by means of Internet Protocol Security (IPsec) (Kent and Seo, 2005).

The stack on the Vehicle ITS-S Host is in charge of executing final applications that could access remote services. As observed, this stack includes a common networking middleware based on the Transport Control Protocol (TCP) and User Datagram Protocol (UDP). An essential part of the host protocol stack is the facilities layer. As can be seen in Fig. 1, a Java Virtual Machine

(Java VM) is used as the basis for the Open Service Gateway Initiative (OSGi) framework. OSGi acts as the manager of the lifecycle of middleware and applications, and makes easier the communication among software modules installed in the host. Using this configuration, a set of ITS applications can be installed to operate on the top of the facilities layer.

The communication stack instantiated in the roadside ITS-S access router acts as network attachment point for vehicles using short/medium-range communication technologies. Similarly to the MR, the available wireless technologies to communicate with vehicles are WiFi (802.11 a/b/g), 802.11p (ETSI G5-compliant) and WiMAX.

Finally, in the upper part of Fig. 1 we can see the communication stacks for both the Central ITS-S Application Server (ITS-S AS) and the Central ITS-S Home Agent (Central ITS-S HA). The former is intended to host ITS application managed by the central ITS-S. The latter is necessary for maintaining the connectivity of vehicles upon the change of point of attachment to the road, acting as NEMO home agent (HA). For this reason, the modules included in the network layer are equivalent to the ones included at the same layer in the MR.

4.2. Proposed Extensions to Support CAM and DENM Facilities

The vehicular communication architecture presented in Section 4.1, which follows the ISO/ETSI guidelines, has been extended with new modules to support both CAM and DENM messaging facilities. In the following, it is explained the different additions proposed for each node to achieve a correct implementation of these facilities, taking into account the corresponding standard specifications (European Telecommunications Standards Institute, 2011, 2010b) as described in Section 2.

4.2.1. CAM Messaging Modules

CAM messages are generated by the Vehicle ITS-S MR and broadcasted using the IEEE 802.11p wireless interface. The Roadside ITS-S AR within the coverage area will receive the CAM messages and forward them to the Central ITS-S AS, where ITS applications are hosted. The Central ITS-S AS decodes CAM messages and the status information contained within the CAM message about the vehicle is made available to the ITS applications. The most noteworthy module is the one implemented in the MR, whose functionality is later covered in more detail.

To achieve this operation, the following modules have been included over the base communication architecture. In the vehicle side, the MR has been provided with a facility layer that operates over a Java basis to host OSGi-based facilities. As depicted in Fig. 1, a new module operating as a facility is included, which is responsible for the generation of CAM messages. The ITS-S AR plays an important role, forwarding the CAM messages received from vehicles in the coverage area to the Central ITS-S. The module covering this capability is included on the top of the facilities layer of the Roadside ITS-S AR.

In the Central ITS-S, the HA entity is not modified, since it works at network level and it is only used in the proposed scenario as a common border router with Internet. Nevertheless, as can be seen in Fig. 1, the Central ITS-S AS does include a facility to decode the CAM messages indirectly received from the vehicles through the Roadside ITS stations.

4.2.2. DENM Messaging Modules

DENM messages are generated by the Central ITS-S AS due to a request from one of the ITS applications requiring the notification of a road event (e.g. a vehicle collision). The geo-dissemination module included in the AS is in charge of distributing the DENM messages to the

Roadside ITS-S ARs within the event area. The selected roadside ITS stations will forward the DENM messages received from the Central ITS-S to the vehicles located under their coverage area. Ultimately, DENM messages are received by the vehicle MR, which forwards them again to the vehicle ITS-S host, since this entity is the responsible for evaluating the event contained in the DENM message and taking the necessary actions.

To achieve this operation, the following extensions are proposed to the base communication architecture. As observed in Fig. 1, the Central ITS-S AS includes a facility to generate DENM messages. This extra module receives requests from ITS applications to geo-disseminate road incidences according to the target area of the event where the DENM notification must be disseminated. This module uses information about the location of installed Roadside ITS-Ss and decides through which ones the DENM notification will be sent to cover the concrete dissemination area. This DENM message is received by the ITS-S AR, which is in charge of managing its retransmission to vehicles.

The ITS-S AR plays an important role since it forwards the DENM messages received from the Central ITS-S to all vehicles within the wireless range of the roadside ITS-S by using IPv6 multicast. The new module implementing these capabilities is showed on the top of the facilities layer of the roadside ITS-S AR.

At the vehicle side, the MR includes a new module in the OSGi-based facilities layer that is in charge of forwarding the DENM messages received from the infrastructure to the Vehicle ITS-S Host. To allow the host to correctly process the received DENM notifications, a new module is also installed at the facilities layer for decoding the content of DENM messages. In our case, for the sake of usability, we have opted for integrating a reference application into the host in order to show the traffic incidences on the road through a graphical interface.

Although there are several possible communication technologies to be used in the communication between vehicles and Roadside ITS-Ss, for the case of the transmission of CAM and DENM packets, the IEEE 802.11p technology is considered to be the most appropriate, since this technology has been optimized for vehicular environments by removing heavy processes like the link-layer association establishment. When vehicles are driving at high speeds this aspect is of paramount importance to assure the highest connection time.

Finally, in the upper layer of the Central ITS-S AS, there are the two ITS applications intended to notify vehicles about road incidences and maintain vehicle tracking information. These reference ITS applications are explained later in Section 6.

5. Implementation of Message Dissemination Facilities

This section provides concrete details about the implementation performed of the CAM and DENM messaging modules described in Section 4.2. The explanations put special emphasis on describing the novel contributions proposed by this research work regarding existing standard specifications.

5.1. CAM Messaging

As described in Section 4.2.1, CAM messages are generated and broadcasted by the Vehicle ITS-S MR through the IEEE 802.11p wireless interface. Roadside ITS-S ARs within the coverage area will receive the CAM messages and forward them to the Central ITS-S AS. Finally, the Central ITS-S AS decodes CAM messages and the status information contained within the CAM message about the vehicle is made available to ITS applications.

The structure of the CAM message is presented in Fig. 2, which is compliant with the ETSI standard (European Telecommunications Standards Institute, 2011). For the sake of clarity, extra optional fields have not been considered because they are not necessary for our envisaged ITS applications for the moment. Apart from the common fields in the header, such as the protocol version, the message identifier (0 for CAM) or the generation time (in milliseconds since January 1st, 1970), the specific information in the message is contained in the body and the reference position parts. A different station identifier is chosen for each vehicular and roadside unit in our case, and the station characteristics are specified accordingly. Our stations are private, since we are not a public authority, and vehicle stations are physically relevant, since they are installed on moving vehicles. All reference position information is taken from GPS but the heading, which is computed by the CAM facility provided in the MR considering the last positions. In European Telecommunications Standards Institute (2011) there is an additional optional field for extra CAM parameters, but it has been obviated since its description in the current version of standard is incomplete.

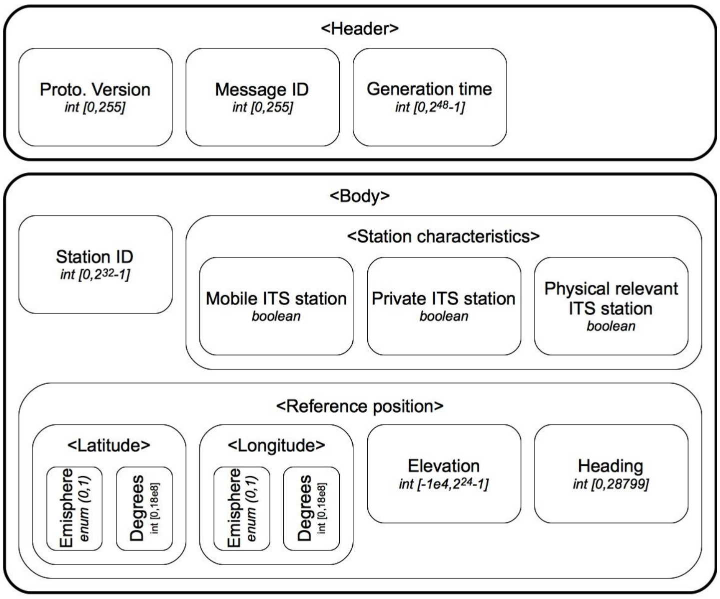


Figure 2: Structure of the CAM message

As previously mentioned, the most important facility regarding the management of CAM messages is included in the Vehicle ITS-S MR. Algorithm 1 details the operation of this module, which is a result of interpreting the textual description given in European Telecommunications Standards Institute (2011). As can be checked, the generation of a new CAM message depends either on the availability of new GPS information or the need to transmit a message after a maximum time. In the first case, there are conditions that have to be satisfied so that a new CAM message is generated, taking as a reference the last one sent: a distance covered threshold ($D\_THRESHOLD$), an orientation change threshold ($H\_THRESHOLD$), and a speed change threshold $S\_THRESHOLD$. The speed is not included at the moment in the finally encoded CAM messages to be sent, but it is saved by the algorithm to simplify the calculations. According

Algorithm 1: CAM message generation algorithm

Input: A new position read p, if any; a record of previous positions $pHist$; the last CAM message sent *lastCam*

Output: A new CAM message is sent and *lastCam* is updated, if applicable; $pHist$ is updated with p, if applicable

```
while true do
    time = System.getTime()
    heading = calcHeading(pHist, p)
    lastPos = lastPosition(pHist)
    lastHist = pHist \ lastPos
    lastHead = calcHeading(lastHist, lastPos)
    speed = calcSpeed(pHist, p)
    if p ≠ null then
        lastSpeed = calcSpeed(lastHist, lastPos)
        if distance(p, lastCam.pos) ≥ D_THRESHOLD or
        |heading - lastCam.heading| ≥ H_THRESHOLD or
        |speed - lastCam.speed| ≥ S_THRESHOLD then
            cam = newCam(time, p, heading, speed)
            sendCam(cam)
            lastCam = cam
        pHist = pHist ∪ p
    else
        p = lastPos
        heading = lastHead
    if time - lastCam.time ≥ T_THRESHOLD then
        cam = newCam(time, p, heading, speed)
        sendCam(cam)
        lastCam = cam
    System.wait(CHECK_PERIOD)
```

to the standard, $D\_THRESHOLD$ is 5 m, $H\_THRESHOLD$ is 4°, $S\_THRESHOLD$ is 1 m/sec, and $T\_THRESHOLD$ is 1 sec. Since the maximum CAM generation rate is 10 Hz according to the standard, the value $CHECK\_PERIOD$ has been established at 100 ms.

5.2. DENM Messaging

As described in 4.2.2, DENM messages are generated by the Central ITS-S AS due to a request from one of the ITS applications requiring the notification of a road event (e.g. a vehicle collision). DENM messages are distributed to the Roadside ITS-S ARs located within the event destination area.

Fig. 3 depicts the structure of the DENM message, which is compliant with the standard specification (European Telecommunications Standards Institute, 2010b). The header is identical to the one included in CAMs, but the body contains more fields. According to the standard specification (see Section 2.2), the body contains a wide set of data elements informing about the event, organized in three different categories: *Decentralized Situation Management Group*, which includes general information about the event; *Descentralized Situation*, which collects specific details about the event informed in the message; and, *Decentralized Situation Location* informing about the event location data.

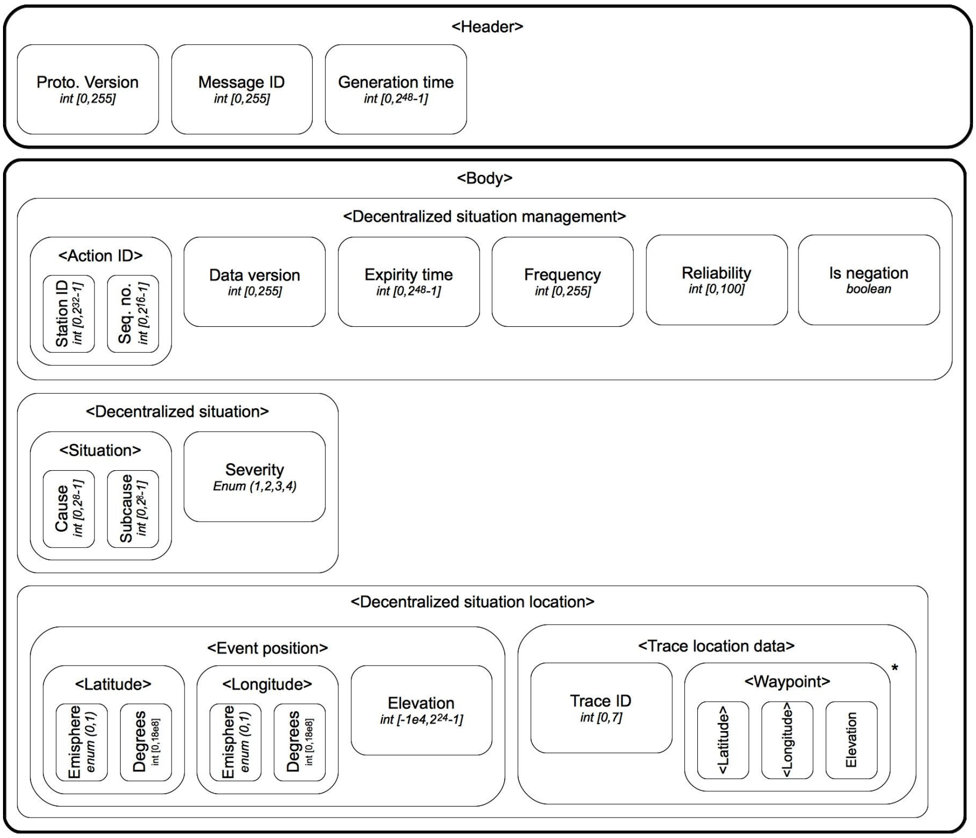


Figure 3: Structure of the DENM message

Unlike the CAM case, the responsibility of distributing DENM messages lies on two entities in our scenario: the Central ITS-S AS and the Roadside ITS-S AR. In the first entity the DENM message is created and distributed to the ARs within the target area where the DENM message needs to be disseminated. The procedure followed in this case is detailed in Algorithm 2. This function is called by a particular ITS application wanting to disseminate an event, and most of the data required to create a DENM message are provided. If a previous DENM message was generated for this event, the data version field should be updated accordingly. With this field it is also possible to indicate the termination of the event, using the value $EVENT\_END$ (255 according to the standard). Moreover, it is needed a mapping between the type of the event provided by ITS application and the required cause and sub-cause fields, and the same with the gravity of the event. As can also be seen, trace waypoints are only created when needed. With all this information, now it is possible to create the new DENM message, specifying the specific ITS-S identifier ($STATION\_ID$), and a generation time of $INVALID\_TIME$ (0 value in our implementation), which is identified by the Roadside ITS-S as a message to be broadcasted for

Algorithm 2: DENM message generation algorithm

```
Input: A new event e is received from one of the applications; a record of the previously
       generated DENMs dHist; a record of the previously generated event traces tHist
Output: A new DENM message is generated and sent to involved Roadside ITS-Ss, if
        applicable; dHist is updated with a new DENM message, if applicable
sequenceNo = generateSequenceNo()
previousDenm = findDenm(dHist, e)
dataVersion = 1
if previousDenm ≠ null then
    if e.termination then
        dataVersion = EVENT_END
    else
        dataVersion = (previousDenm.dataVersion + 1) % 256
    delDenm(dHist, previousDenm)
mapSituationCause(e.type, ref cause, ref subcause)
mapSeverity(e.gravity, ref severity)
trace = findTrace(tHist, e.waypositions)
if trace == null then
    trace = newTrace(e.waypositions)
    tHist = tHist ∪ trace
denm = newDenm(INVALID_TIME, STATION_ID, sequenceNo, dataVersion,
e.expiryTime, e.frequency, e.reliability, cause, subcause, severity, e.pos, trace)
rsus = findRsusInEvent(e.pos, e.dissZone)
sendDenm(denm, rsus)
if previousDenm == null then
    dHist = dHist ∪ denm
```

the first time. Finally, it is needed to find the Roadside ITS-Ss within the dissemination area of the event. For this search, the area provided by the ITS application is considered, although this information is not included in the DENM message because the current version of the standard does not specify this part of the message yet.

On the other hand, the Roadside ITS-S AR executes the code presented in Algorithm 3, as part of its DENM forwarder module. In this procedure the AR continuously checks the frequency of active events before retransmitting a new DENM message within the coverage area. When a DENM is received from the Central ITS-S AS, it is added to list of active events if it did not exist. Once the event has passed the expiration time or if it includes a data version indicating the end of the event, the corresponding DENM message is removed from the list of active events. The algorithm uses a constant called *CHECK_PERIOD* which indicates the algorithm execution periodicity. It is worth mentioning that the current version of the standard does not specify the usage of this kind of constant. Nevertheless, we have found it essential to achieve an optimal execution of the dissemination process.

Algorithm 3: DENM message retransmission algorithm

```
Input: A new DENM d is received from the Central ITS-S, if any; a record of previous
       DENMs dHist
Output: A DENM message is retransmitted, if applicable; dHist is updated with d, if
        applicable
while true do
    time = System.getTime()
    if d ≠ null then
        previousDenm = findDenm(dHist, d)
        if previousDenm ≠ null then
            delDenm(dHist, previousDenm)
        dHist = dHist ∪ d
    for each previousDenm ∈ dHist do
        if previousDenm.expiryTime < time and
        previousDenm.dataVersion ≠ EVENT_END then
            if previousDenm.time == INVALID_TIME or
            currentTime - previousDenm.time ≥ 1/previousDenm.frequency then
                previousEvent.time = time
                sendDenm(previousDenm)
        else
            removeDenm(previousDenm, dHist)
    System.wait(CHECK_PERIOD)
```

6. Reference ITS Applications

The CAM and DENM facilities provided by the modules previously described have been used for developing two ITS applications. On the one hand, a vehicle tracking and tracing service has been implemented to take advantage of the CAM messaging. On the other, a road incidence notification service has been developed with the aim of using DENM messaging. This part of the article details these two reference applications that have been developed in order to validate the CAM and DENM messaging capabilities claimed by the corresponding standard specifications.

6.1. Vehicle Tracking Service

The vehicle tracking service is mainly oriented to support a backend system requiring tracking and tracing information of vehicles along the road infrastructure. This information may be necessary to collect statistics about road usage or can be used as input to provide value-added services to the vehicles. For this reason, although it is identified as a final application on the top of the Central ITS-S AS, it is also an application that can be used by local or third party entities like, for example, a logistic company. In fact, this ITS application provides a Web service interface that can be accessed by external entities to request vehicle tracking and tracing information.

The basic operation of the vehicle tracking service is as follows. The information received from the Roadside ITS-S ARs about CAM messages is used to maintain a data base of the vehicles positions and status during a timeframe. This way, when the vehicle tracking service receives the solicitation of providing tracking information of a specific vehicle, it accesses to this record to provide an answer. More precisely, the vehicle tracking software offers the following Web services to third party entities:

- *Continuous vehicle tracking*. This feature allows a service to subscribe for receiving asynchronous notifications about the location of a specific vehicle.
- *Entry/exit vehicle tracking*. This allows a particular service to subscribe to a specific geo-fencing area so that it is informed when a vehicle enters or leaves the concrete zone.
- *Vehicle within geographical area*. Specifying an area, the service can gather information about all the vehicles driving within the zone.

As observed, some of these services are based on a subscription model so that third parties are informed about asynchronous tracking events in which they are interested. The areas are identified in the current implementation by a circular zone determined by the geographical coordinates of the centre and the radius in meters. On the other hand, all vehicles are identified with the same value used as ITS-S identifier in CAM messages.

This vehicle tracking application has been used in the FOTsis project [1] to assist the operation of two real ITS applications widely evaluated in real roads: Special Vehicle Tracking, to notify the infrastructure and surrounding vehicles about the path followed by a special vehicle (usually trucks transporting dangerous goods); and, Advanced Enforcement, which continuously gathers status information about vehicles to assure their compliance with applicable traffic regulations. The first stage of these trials are described in a FOTsis deliverable (Kurano et al., 2013).

Fig. 4 shows a Web application implemented for testing purposes that uses the vehicle tracking features previously described together with Google Maps. In this particular case, the screenshots provided show the usage of the entry/exit vehicle tracking feature, where the user receives an alert when a vehicle enters and later leaves a geo-fencing area defined in a testing scenario later described in Section 7.

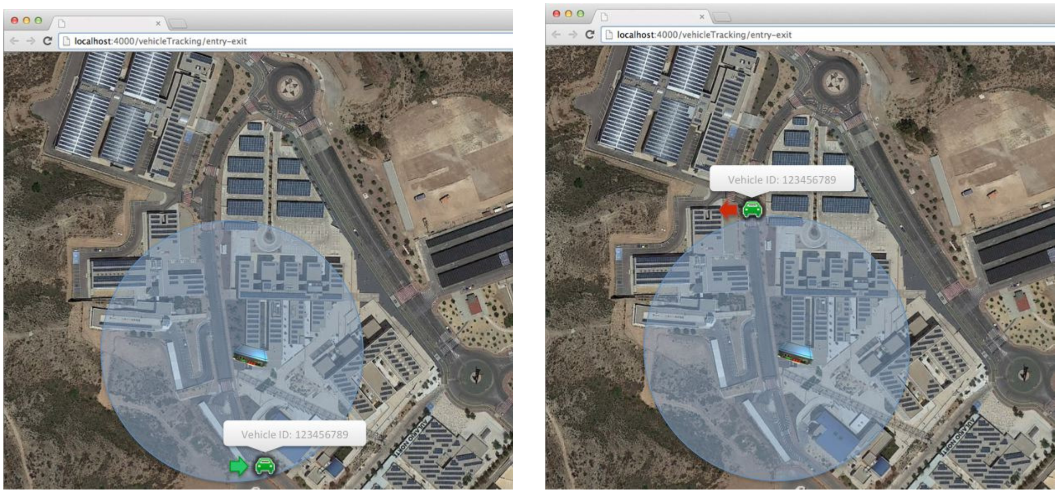
6.2. Road Incidences Service

Unlike the previous one, this ITS service requires to install functionality in both the Central ITS-S and Vehicle ITS-S. This can be clearly seen in Fig. 1, where, apart from a software module included in the AS side, there is another in the Vehicle ITS-S Host.

An application being executed in the Central ITS-S AS can use the road incidences service to distribute asynchronous notifications to vehicles driving within a specific geographic area. Upon the reception of the request, the road incidences service uses the geo-dissemination facility to solicit the propagation of the content of the notification using a DENM message. This facility distributes the DENM message among the Roadside ITS-Ss falling within the area where the event needs to be disseminated.

Following a design similar to the one described for the vehicle tracking application, the road incidences application provides a Web service interface that can be accessed by third party entities. Through this interface, other ITS applications can solicit the dissemination of road incidences. Upon receiving such a solicitation, the ITS road incidences service receives basic information of the event such as type, reference position of the event, action area, duration or

[1] http://www.fotsis.com



(a) Vehicle entrance in the geo-fencing area

(b) Vehicle exiting from the geo-fencing area

Figure 4: Screenshots of a Web application using the entry/exit vehicle tracking capability

notification frequency. The type of the event is coded as an integer value indicating different notification types, while the areas are coded as in the vehicle tracking case. According to the DENM message generation algorithm described above, this information is used to fill a DENM message to be disseminated within the target area.

At the vehicle side, the application included in the Vehicle ITS-S Host receives DENM messages and processes the notifications. To improve the usability of the application, a reference graphical front-end has been implemented here for Android mobile devices, so that users can be aware of the incidence by observing a map. A screenshot of this application is showed in Fig. 5. By using Google Maps the driver is warned about the presence of an event. In this case it is a road works incidence near the position of the vehicle.

The road incidences software has been also used in the FOTsis project, within the Safety Incident Management service, which provides real time information to drivers about incidences on the road. This service is under real tests in the Spanish M12 highway during winter 2013/2014 and, in fact, it has been used as the source of incidence information in the execution showed in Fig. 5 to validate the road incidences software.

7. Experimental Evaluation

The CAM/DENM messaging facilities developed in this paper have been deployed in a testbed with the aim of evaluating its operation in real conditions. For this evaluation the services described above have been used to generate CAM and DENM traffic that allow the experimental assessment of the messaging middleware in a real driving environment.

7.1. Test-Bed

The set-up testbed depicted in Fig. 6 has been deployed at the University of Murcia (UMU). As can be seen, the three types of ITS station are included and the main entities have been included, according to the network architecture presented in Section 4. Fig. 7 shows the equipment

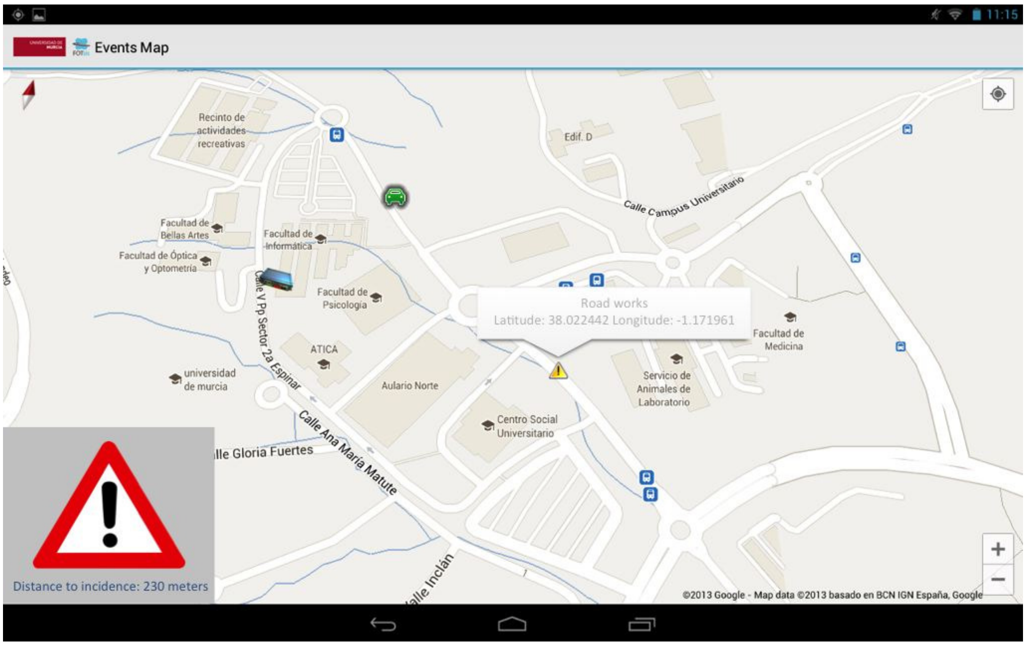


Figure 5: Screenshot of the Road Incidences vehicle application

used at the installation point. The Roadside ITS-S has been placed on the roof of the Faculty of Computer Engineering, while the Central ITS-S is set-up in a close laboratory inside the building. A common vehicle from the UMU fleet is used for mounting the MR and host entities aboard, while the antenna is affixed with a magnetic base on the vehicle roof. For the sake of clarity, all the components used in the testbed are listed in Table 1.

The Vehicle ITS-S is powered with a Mobile Router offering external connectivity to in-vehicle hosts through a common WiFi connection based on IEEE 802.11g that is provided by the same unit. The connection between the MR and the AR is carried out by means of IEEE 802.11p, using the control channel of the ETSI G5 profile (European Telecommunications Standards Institute, 2009a). The vehicle roof-mounted antenna showed in Fig. 7c is used to improve the communication signal with the AR. As can be seen in Table 1, the same unit is used for both the MR and the AR. However, for the Roadside ITS-S, a stick antenna providing a better performance is used. As can be seen in Fig. 7a, it has been affixed to a tripod located near the corner of the faculty roof, with the aim of improving the coverage with vehicles passing nearby.

While the communication between the MR and the AR is performed over the 802.11p link, a direct wired connection is used between the AR and the indoor laboratory where the Central ITS-S is mounted. Here a high-end router interconnects the roadside network segment with the AS. This router only performs the interconnection tasks assigned to the Central ITS-S Home Agent, since IPv6 mobility is not used in the testbed. The reference services explained in the previous section are hosted in the AS.

CAM and DENM messages are exchanged between AR and AS using a common TCP connection over IPv6. However, CAM and DENM messages are exchanged between MR and AR using UDP datagrams that are destined to the well-known IPv6 multicast address referring to

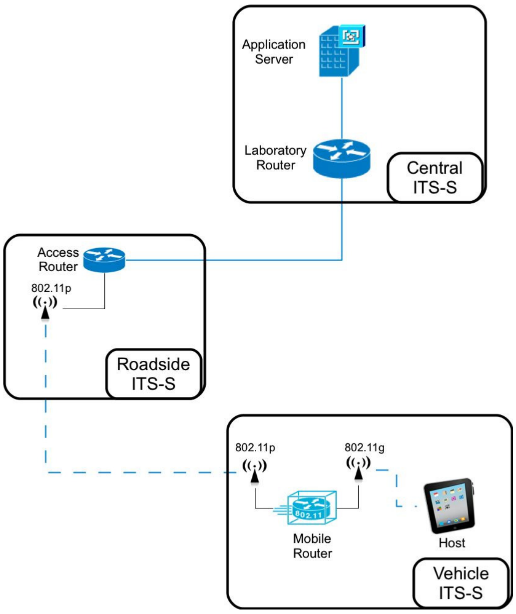


Figure 6: Testbed deployed at University of Murcia

Table 1: List of hardware equipment used in the testbed

Networked nodes	
Node	**Model**
Vehicle Host	Samsung Galaxy Tab 2
Mobile Router	Commsignia LGN-00-11
Access Router	Commsignia LGN-00-11
Laboratory Router	Cisco 3700 Series
Application Server	i5 3.1Ghz/3GB, Ubuntu 10.4
Communications hardware	
Item	**Model**
802.11p transceivers	Unex DCMA-86P2 mini-PCI (in AR and MR)
Vehicle antenna	Omni-combined 3G/11p/GPS 7dBi
Roadside antenna	Omni-stick 12dBi
Relevant software	
Feature	**Description**
ASN.1 parser	ASN Lab ASN.1 Java compiler
Java in AS	Oracle Java SE 1.6
Java in MR and AR	Oracle Java SE Embedded 1.6
Web services	Apache CXF

all the nodes present on the local network segment (*ff02::1*). The use of this transport is based on the fact that there is no sense in using a connection-oriented transport since vehicles enter sporadically in an AR communication range.

(a) Roadside ITS-S AR (b) Car from the UMU fleet

(c) Combined vehicle antenna (d) Vehicle ITS-S MR

Figure 7: Equipment used in the testbed

7.2. Testing Plan

Using the aforementioned testbed we have evaluated the performance of the CAM/DENM messaging facilities. More precisely, our intention has been analyzing the influence in both facilities of aspects such as vehicle speed, signal quality, message dissemination rules, etc. To this end, in the different tests we have conducted, the following performance indicators has been collected:

- *Packet delivery ratio (PDR)*. This is the number of CAM and DENM messages received attending to all the messages transmitted by the sender.
- *Received signal strength indicator (RSSI)*. This value has been chosen to evaluate the signal quality level in the vehicle MR.
- *Connection time with the AR*. This is the time elapsed between the first correctly delivered message and the last one.

Table 2: Number of trials carried out in the circuit for each configuration

Speed	CAM_fix	CAM_stand	DENM
10 Km/h	n/a	n/a	10
20 Km/h	10	10	10
30 Km/h	10	10	10
40 Km/h	10	10	10

- *Connection distance with the AR*. Distance between the vehicle positions obtained with the first and last messages correctly delivered.
- *Messages transmitted*. This allows us to evaluate the advantage of using the standardized message generation rules for CAM, instead of a fix transmission rate.

The bandwidth and delay of the network are not evaluated, since they are not found essential performance indicators in this work. In fact, they have already been proved to be enough for CAM and DENM messaging, according to prior tests presented in Santa et al. (2014). In this prior work, a bandwidth above 2 Mbps and round-trip delay times bellow 10 ms are obtained within the 802.11p coverage area.

Moreover, with the aim of obtaining performance results with different configurations, a pair of *testing variables* have been considered, apart from common variable factors such as the terminal position and time:

- *Driving speed*. The relative speed between a pair of moving network nodes is known to be an issue in wireless communications, due to layer-two adaptation capabilities of nodes and physical phenomena, such as the Doppler effect.
- *CAM transmission algorithm*. The usage of the CAM generation algorithm proposed in Section 5.1, as opposed to a fix generation rate used in other proposals for simplicity, should impact on the network needs.

Bearing in mind the previous parameters, a set of moving trials were planned in a real driving environment in order to test different configurations. The scenario considered is illustrated in Fig. 8. In the map it is identified the position of the Roadside ITS-S and a set of signal obstruction locations later discussed. The vehicle performs a circular itinerary to cross the AR coverage area. In the image, it is remarked the stretch under evaluation that, as it is later showed, assures the evaluation of the whole connectivity with the AR, starting and ending with null coverage. In the results collected, the logs have been filtered to only consider this particular stretch.

In order to obtain significant results, each possible configuration was individually evaluated through a set of laps in the circuit. This way it is possible to average the performance indicators obtained per test case. The different configurations considered and the laps performed in the circuit are listed in Table 2. A total number of 100 laps were completed in an intense evaluation campaign performed in July 2013 during two weeks. The speed analysis has been performed between 10 and 40 km/h, since it is not possible to drive faster in the area, due to the speed limit and the presence of turns, roundabouts and speed bumps. For the case of DENM the slowest speed is used with the aim of gathering more messages within the reference road stretch at 10 Km/h, since the transmission ratio was adjusted at a slower value than in the CAM case.

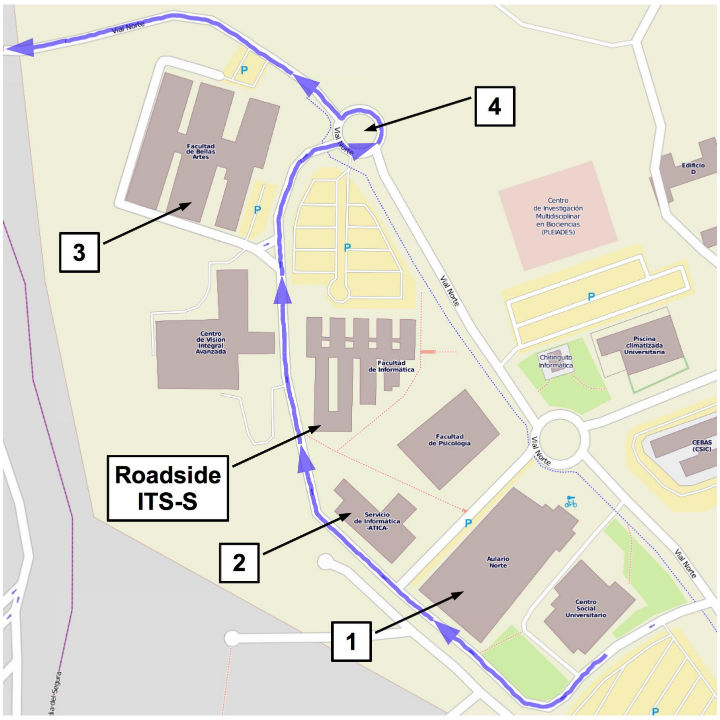


Figure 8: Testing scenario in the university campus

CAM messaging is analyzed considering both a fix transmission rate (*CAM_fix*) of 10 Hz and using the sending rules recommended by ETSI (*CAM_std*), following the algorithm described in Section 5.1. For the case of DENM, the message retransmission algorithm described in Section 5.2 is used by the AR, given a event previously notified by the AS. In practice, to make easier the evaluation, an event with an expiry time in the far future and a transmission frequency of 1 Hz is used to guarantee a periodic transmission of DENM messages.

The size of the CAM and DENM messages sent were 26 and 49 bytes, respectively. Given that 8 bytes are needed by the UDP header, the total sizes of the datagrams sent were 34 bytes for CAM and 57 bytes for DENM. All the messages sent and received were logged by both MR and AR, together with the perceived RSSI and the GPS vehicle position. This way it has been possible to compute all the performance indicators previously listed.

7.3. Analysis of Results

This section presents the results gathered during the testing campaign described in the previous section. We firstly analyze the radio coverage of the communication area, which is necessary to evaluate the results obtained in the transmission of CAM (vehicle to infrastructure or uplink) and DENM (infrastructure to vehicle or downlink).

7.3.1. Signal quality

As a first step for understanding the network results presented later, it is important to consider the signal quality when a moving vehicle connects with the AR. For this, the RSSI measurements

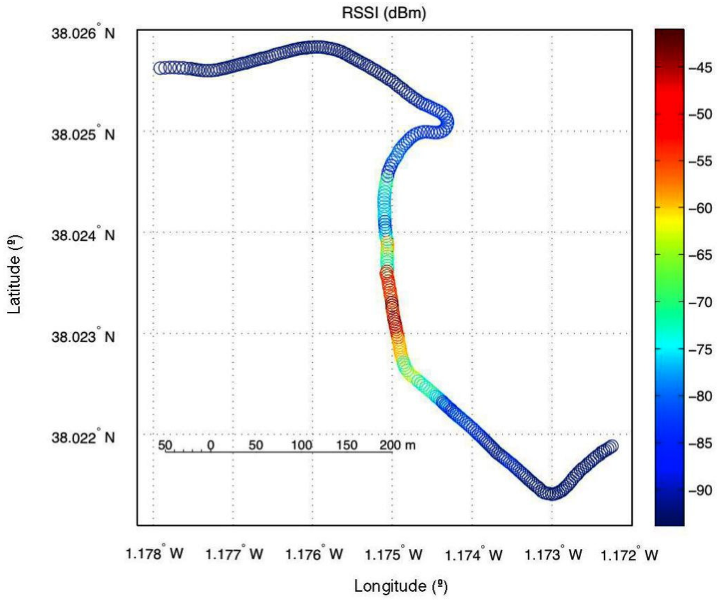


Figure 9: RSSI perceived by the MR

provided by the 802.11p device driver is periodically logged in the vehicle MR. Fig. 9 shows the perceived RSSI while the vehicle is moving in the road stretch depicted in Fig. 8 and CAM messages are emitted at the maximum rate specified in the standard (i.e. 10 Hz). These values have been obtained at a very low speed (below 10 km/h) due to RSSI values are updated at a maximum rate of 1 Hz. The GPS coordinates are also updated in all trials at a rate of 1 Hz, but in this case the trajectory is smoothed by interpolating intermediate positions, thus removing repeated pairs of latitude - longitude in all the records collected within the same second.

The RSSI results show that, at the starting point of the stretch, the coverage can be considered null (around -90 dBm), due to the two buildings blocking the signal (marked as “1” and “2” in Fig. 8). When the vehicle reaches the second building the coverage improves, and reaches its maximum level of -47 dBm when the vehicle is positioned just aside the ITS-S Roadside AR. After this point, the coverage starts to get worse again, due to the increase of the distance to the antenna and the loss of the line of sight with the vehicle. However, this effect is soften by the progressive altitude increase until the end of the stretch. At location marked as “4” in Fig. 8 the vehicle turns to almost lose connectivity and later, when it pass the building marked as “3”, the coverage gets null due to the lack of line of sight with the antenna and the increasing distance with the AR.

These RSSI analysis confirms the high dependence of the results on the line of sight with the AR. Due to the frequency range in which 802.11p operates (5.9 GHz), buildings, other vehicles or vegetation can block the signal impacting on the measured RSSI. Moreover, in this particular scenario, the relative altitude between the vehicle and the AR is another important factor. This reveals that the orography of the area is an extra issue to be considered when selecting the installation point of roadside stations at inter-urban locations, above all.

Table 3: Averaged performance indicators under a fix CAM sending ratio of 10 Hz

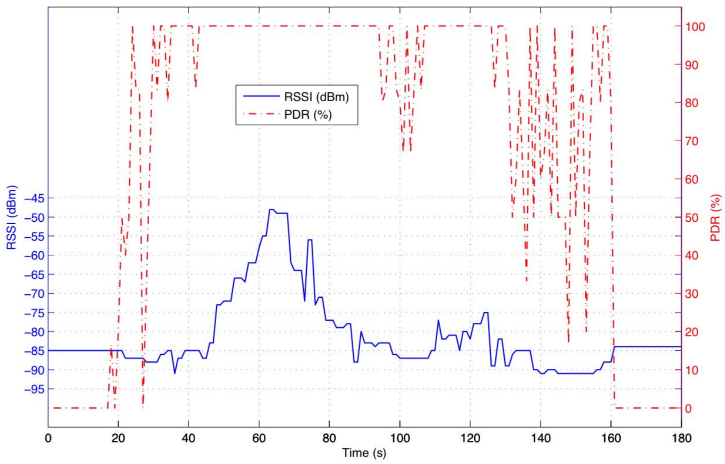
Speed	**PDR (%)**	**PDR STD**	**Real speed (Km/h)**	**RSSI (dBm)**	**Conn. time (s)**	**Conn. distance (m)**
20 Km/h	70.83	40.60	19.21	-80.35	141.80	572.57
30 Km/h	65.75	41.56	27.21	-81.00	99.70	568.53
40 Km/h	65.41	41.41	33.93	-83.17	79.90	574.82

7.3.2. CAM performance

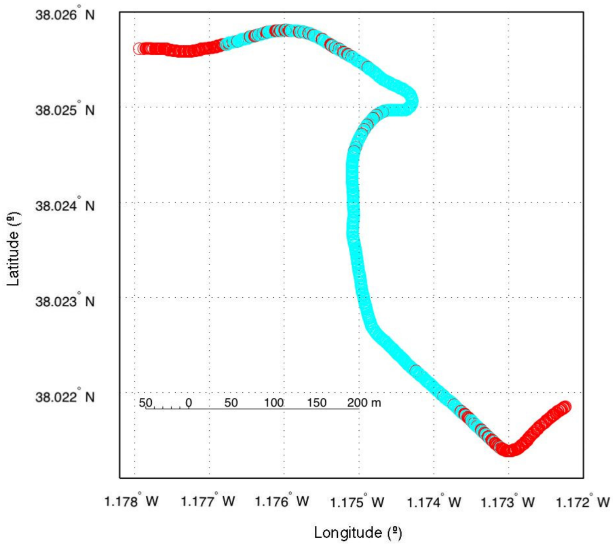
As expected, the PDR of CAM messages is highly affected by the signal quality perceived with the AR. This is showed in Fig. 10a. This graph, for a lap carried out at 20 km/h with a fixed CAM generation rate, illustrates the PDR and RSSI values, which are averaged per second. Alternatively, Fig. 10b plots the messages correctly delivered and lost during the same trial. As can be noted, there is a correspondence between the RSSI values showed in Fig. 10a and the ones showed in the coverage study in Fig. 9. The better performance is obtained when the vehicle moves near the AR antenna, and PDR values of 0% are obtained at the beginning and final parts of the stretch. Intermediate PDR values are obtained when the vehicle approaches the AR and later, when the light of sight with the antenna is affected around time 100s. Just after this point, the coverage improves at the roundabout due to the positive slope of the road, as said before, and thus a better PDR performance is noticeable. When the signal gets obstructed by the building marked as "3" in Fig. 8 a greater number of messages start to get lost and the PDR falls until 0%.

A global view of the results obtained in the different tests conducted to examine the behaviour of CAM messaging can be seen in Table 3. During these tests, the CAM generation model has followed the fixed scheme where CAM messages are generated at a fixed rate of 10 Hz (maximum rate allowed by the standard). We have opted by using this configuration because by maintaining a periodic and high data rate it is possible to better assess the performance of this messaging facility. Nevertheless, it is worth noting that these results consider small coverage gaps at the beginning and end of the stretch. The results show a better PDR at lower speeds, although the most interesting performance decrease is showed between the 20 and 30 Km/h. Attending to the real averaged speed, it can be seen that the most relevant variation in mobility is also between the first and second case. This is due to maintaining higher speeds is gradually more difficult, due to roundabouts, speed bombs and zebra crossings, above all. Moreover, it is later confirmed in the DENM results that greater changes in the network performance due to movement speed are especially noticeable at lower speeds. The standard deviation of PDR values also gets worse with high speeds (this is also confirmed later in the DENM performance analysis), but at 40 Km/h it slightly decreases. This is explained by the fact that, at higher speeds, obtaining intermediate PDR values during the trial at a fixed message generation rate is rarer, due to areas of low coverage are passed faster.

Regarding the RSSI in the fifth column of Table 3, we can appreciate how there is a direct relation between the speed and the signal level perceived by the vehicle due to mobility. Finally, the last two columns provide the connection time with the AR and the connection distance in the stretch. As expected, the connection time decreases with the moving speed, but reveals that messages can be exchanged for almost 80 seconds in the 40 km/h case. Together with a communication range around 570 meters in this challenging environment with altitude variations and building blocks, we can say that a good coverage is provided by the AR. However, it should



(a) PDR against signal quality



(b) Packets received and lost

Figure 10: CAM packet delivery ratio at 20 Km/h

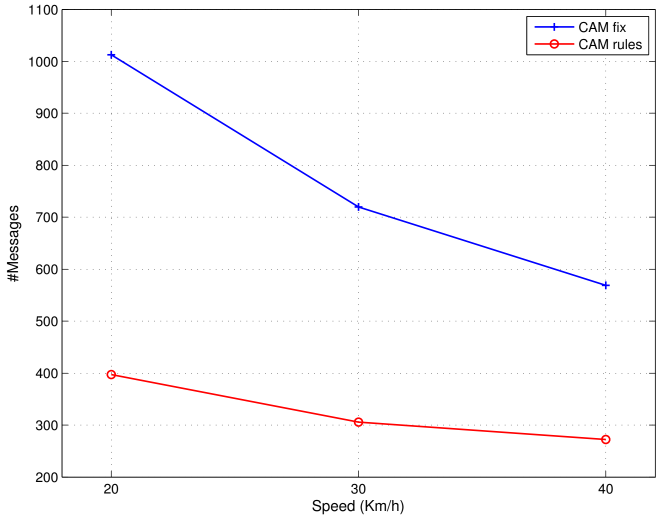
be taken into account that this range is directly calculated as the euclidean distance between the first and last logged positions of the vehicle in a CAM message, but the real distance covered on the road is higher due to the appreciable curves in the scenario. Although the averaged range is slightly better at 40 Km/h, it is expected that, in general, greater ranges are obtained at lower speeds, due to the higher probability of receiving more messages during the time that the vehicle moves at further locations with a poor signal quality. This is later confirmed in the DENM case.

Another final aspect worth evaluating about the CAM messaging facility is the impact of using the CAM generation rules suggested by the standard specification, compared with a basic scheme generating CAM messages at a constant frequency. For this reason, the total number of messages sent using our implementation of the standard (Algorithm 1) are showed in Fig. 11a, as compared with the case of generating messages at a fixed rate of 10 Hz. The first impression is that the number of messages when using the generation rules has been greatly diminished. This is due to a new message is sent only when a specific condition is met: either one second elapses or there is a significant change in the distance covered, the driving heading or the speed. In the fixed generation case the graph also shows an appreciable decrease in the number of CAM messages sent during the trial as the speed increases, which is easily explained by the lower testing time. Conversely, the use of the standard generation rules implies a slower decrease of messages sent. Given the particular scenario under study, this is explained by the fact that increasing the speed also implies greater changes in the distance covered and the speed, due to acceleration and breaking. A graphical representation of this behavior is showed in Fig. 11b, which plots the CAM messages sent during two laps at 30 km/h using the two configurations. Apart from the clear difference in the number of transmissions in both cases, we can appreciate how, when using the standard generation rules, more messages are sent at curves and the roundabout, due to changes in heading and speed, respectively. Stretches with less density of messages belong to periods of straight driving at constant speed. According to the log recorded at these locations, these messages have been generated due to the distance covered rule. Here there are also small periods with a higher density of messages that belong to locations were the vehicle has to vary the speed, due to the poor quality of the pavement and speed bumps.

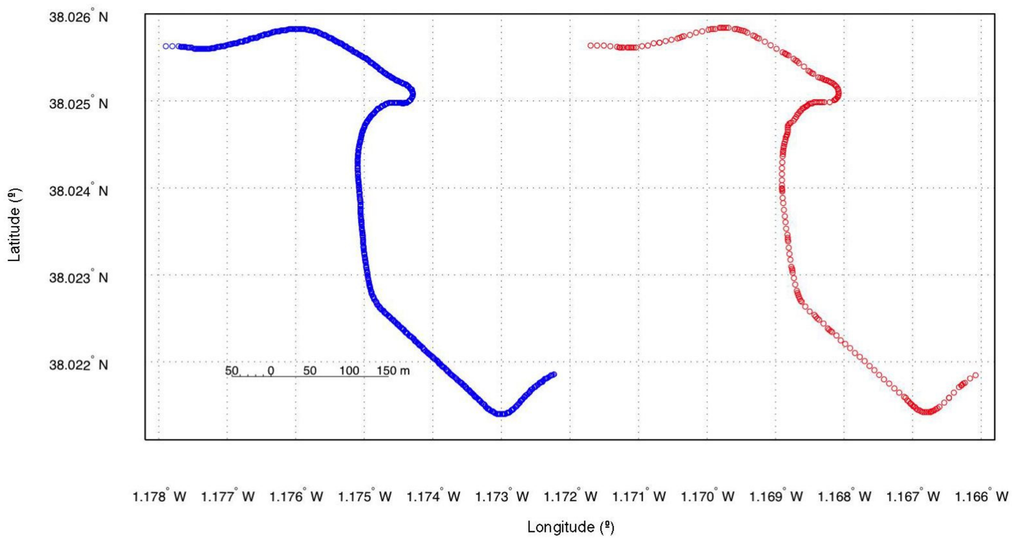
7.3.3. DENM performance

The packet delivery results obtained in the DENM case are showed in Fig. 12b. It is important to bear in mind that for the case of DENM messaging, the message generation rate was limited at a 1 Hz. this way, PDR values are not averaged since each record contains information about an individual packet (received or not received). Fig. 12a shows the PDR together with the RSSI perceived in the vehicle. As can be seen, the results are quite similar to the CAM case. To make easier the comparison with Fig. 10a, a lap at 20 km/h has been also chosen in this case. The slight differences in the RSSI lines in both figures is again due to this value is not averaged now. However, it has been detected that the channel is more stable in DENM evaluations during the time the vehicle moves near the AR antenna. This is attributed to the location of the sender node, which now static and installed on the top of a building, thus improving the visibility in the road stretch. This way, the small PDR decrease that is noticeable around time 100s in Fig. 10a is not visible now before reaching the roundabout. This can be also checked in Fig. 12b.

An interesting effect observed in the DENM case, as compared with the CAM study, is that the maximum coverage range has been slightly diminished. This can be seen graphically comparing the packets correctly delivered in Fig. 10b and Fig. 12b. At the beginning of the reference stretch the messages start to be received later, but this difference is further visible at the end, where packets are hardly delivered as soon as the vehicle reaches the building marked as "3" in Fig. 8. In averaged numbers, this is also noticeable in Table 4, where the connection time and distance values are smaller in all cases for downlink transmissions. Although the delivery of messages in the area next to the AR has been improved, the packets are not correctly received at farther locations. This can be explained by attending to the hardware used in both the vehicle and the roadside ITS-S. While the vehicle antenna gain is 7 dBi, for the roadside unit it is 12 dBi. This makes the AR more capable of correctly decoding messages received with a poor signal quality. In this way, the vehicle to roadside network segment works better than the roadside to



(a) Total number of messages sent

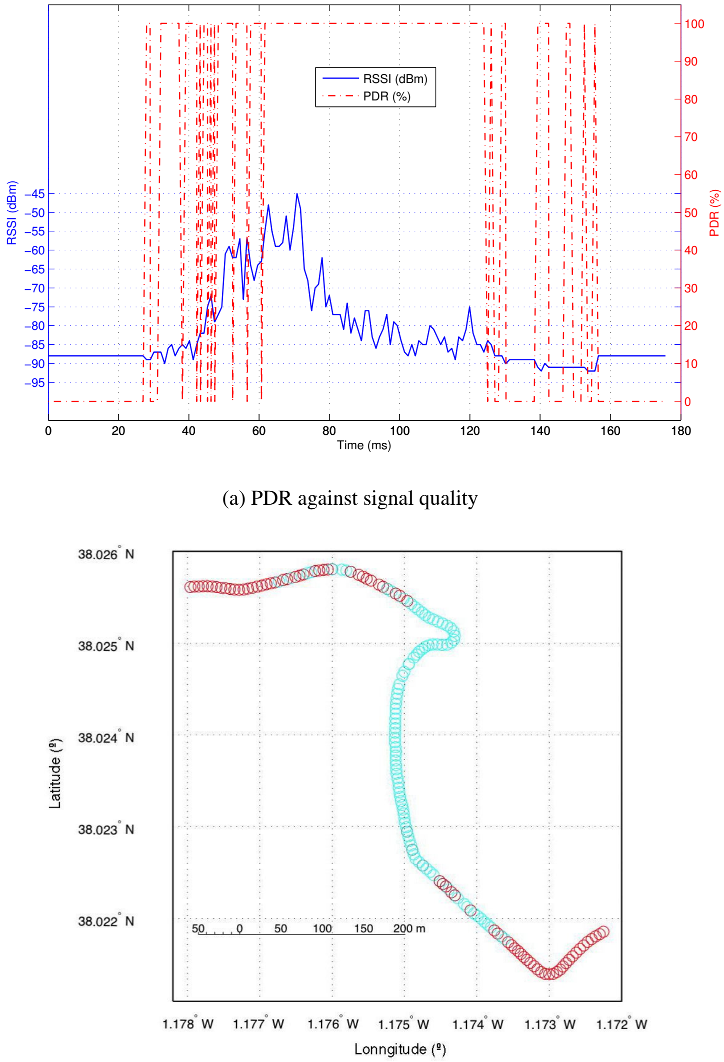


(b) Messages sent during a trial example using a fix generation rate (left) and the generation rules (right)

Figure 11: Messages transmitted with a fix CAM generation rate and using generation rules

vehicle one in this particular scenario.

The rest of the values showed in Table 4 indicate that the medium PDR values per speed are lower than in the CAM case, given that many packets are lost at the start and end of the stretch. However, within the DENM tests, the results are again better for slower speeds. The standard deviation of PDR results are also better at 40 Km/h, breaking the tendency. As concluded for



(a) PDR against signal quality

(b) Packets received and lost

Figure 12: DENM Packet delivery ratio at 20 Km/h

the CAM evaluation, at higher speeds less messages are sent for the same space, and the areas where the signal quality is not very good are passed faster, avoiding the collection of alternative sequences of packets received and not received.

7.4. *Summary of results*

Both the uplink and downlink communication segments have been tested in a hybrid scenario (neither urban nor highway) by sending CAM and DENM messages, respectively, and using standardized packets as well as message generation rules. The number of trials have served to

Table 4: Averaged performance indicators under a fix DENM sending ratio of 1 Hz

Speed	PDR (%)	PDR STD	Real speed (Km/h)	RSSI (dBm)	Conn. time (s)	Conn. distance (m)
10 Km/h	58.70	49.71	9.78	-81.74	262.53	523.62
20 Km/h	56.92	49.87	19.29	-81.07	128.50	515.77
30 Km/h	55.71	49.99	27.76	-82.36	81.85	482.32
40 Km/h	55.61	49.95	33.86	-82.80	69.50	498.87

extensively validate the performance of CAM/DENM messaging functionalities. To summarize, in the following the most important conclusions are extracted:

- A strong line of sight dependency has been experienced when using IEEE 802.11p communication technology, experiencing low or even null connectivity when the signal is blocked by large objects such as buildings, above all.
- In the same way, the relative altitude between sender and receiver affects the signal quality and thus the communication performance.
- The packet delivery ratio highly depends on the signal quality and on the capabilities of the hardware employed for wireless transmission.
- The movement speed impacts on the PDR in such a manner that PDR gets worse at higher speeds. Nevertheless, this impact has been proven to be reduced.
- The usage of message generation rules for CAM, compared to fixed generation schemes, saves network resources and allows the Vehicle ITS-S to communicate only status information when it is necessary.
- Connection times between 260 and 70 seconds have been collected for speeds among 10 and 40 km/h, which is time enough to support the eventual transmission of high volumes of data, the communication of location-aware information in the area (as CAM/DENM traffic) or the usage of data mules in delay tolerant network designs, for instance.

8. Conclusion

This paper describes an ITS communication architecture provided with a set of modules for supporting CAM and DENM messaging functionalities. Recent ISO and ETSI standards have been published suggesting a reference framework for deploying CAM/DENM facilities among Vehicle, Roadside and Central ITS Stations. Being compliant with such specifications, the data packet format chosen and message generation algorithms have been described in such a way that they can be a reference in the cooperative vehicles research field. However, there are additional features in the architecture presented that extend the current standards, such as the usage of IPv6 for transmitting CAM/DENM messages, the way these messages are routed to target areas and nodes, or the provision of Web services accesible by third-parties on the Internet. As a proof of concept of the whole architecture, two generic ITS applications have been developed on the top of these CAM/DENM facilities to solve two well-known needs in vehicular environments: detecting the entrance of vehicles in a geo-fencing area, track their current position and providing historical tracing information; and disseminating asynchronous events within a specific geographical area. These two infrastructure-based applications can operate in a standalone way, but they have been developed to allow external third parties the access to these services of general interest.

Apart from the design and implementation of the described software, the whole communication architecture has been instantiated in a testbed deployed at the campus of the University of Murcia. This testbed has been used for the experimental evaluation of the proposal in a testing campaign for analyzing the performance of CAM and DENM messaging services under a real driving scenario. The results reveal that the ITS applications developed in the paper can operate efficiently by using the CAM/DENM functionalities, but also other location-aware or connection-sporadic services can be supported, which can profit from a roadside point of attachment to the wired network. A semi-urban connectivity stretch of about 500 meters has been identified, and vehicles driving at urban speeds can remain connected to the network for about 100 seconds. However, a strong line of sight dependency has been detected and the expectable successful packet deliveries depend on the signal quality, which can be improved by chosen the proper hardware and seeking for a favorable roadside installation point with good visibility. Additionally, for the case of CAM-based services, the usage of the CAM generation rules described by ETSI (European Telecommunications Standards Institute, 2011) has been identified as a key factor to save network resources by sending only relevant data updates about the vehicle status.

Several parts of the architecture described in the work are subject of further research in the short and medium term. The geo-dissemination strategy is intended to be substituted in the future by a geo-multicast approach that improves the efficiency when a number of events are notified from a Central ITS Station. This will avoid the replication of messages from the Central ITS-S AS when more than one Roadside ITS Station falls in the notification area of an event. Moreover, regarding the evaluation part, an interesting testing variable that will be taken into account in future works is the number of vehicles moving in the area, given that the congestion of the wireless medium is an issue in vehicular scenarios with high density of nodes. In the same line, the installation of the testbed near a highway would allow the evaluation of the network at higher speeds (up to 120 km/h). This will be considered in future testing campaigns to assess more widely the impact of vehicle speed in the network performance. Finally, another aspect worth analyzing is the CAM/DENM performance when used in an vehicle-to-vehicle fashion, which requires the combination of these messaging facilities with a geographical routing protocol able to guide the dissemination of messages in a specific area through the vehicular ad-hoc network.

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