A Network Centric Simulation Environment for CALM-based Cooperative Vehicular Systems

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ABSTRACT

The concept of Intelligent Transportation Systems (ITS) presents new R&D challenges in the transportation and ICT sectors and is currently receiving considerable interest from the research community. The primary objective of ITS is the creation of advanced road traffic systems for improved traffic safety, efficiency, and travelling comfort. Applications such as trip planning, automatic tolling and emergency warnings, among others, are envisaged in a system which can potentially reform modern transportation. Basic vehicle and roadside infrastructure collaboration allows an increase in efficiency and safety and acts as a foundation for an extensive application set to achieve these ITS goals. The use of software tools to simulate the behaviour of a network, and then analysing the effect of various parameters on the network performance, is a crucial task for these new technologies' application development and implementation. Currently, since neither infrastructure nor communications capabilities exist in vehicles beyond small scale prototypes, computer simulation is the only viable option in evaluation of potential ITS solutions. This paper presents CALMnet a comprehensive network-centric simulation environment for CALM-based cooperative vehicular systems. Using the OPNET modeler simulation tool, a number of elements necessary for accurate emulation of the complex cooperative vehicular network are identified and addressed. Important areas of consideration include vehicle mobility, communications channel behaviour, application design sets and RSU and OBU device modelling to accurately simulate the envisaged ITS concept.

Categories and Subject Descriptors

I.6.8 [**Simulation and Modelling**]: Types of simulation – *discrete event*

General Terms

Performance, Design, Experimentation

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Keywords

ITS, CALM, WAVE, 802.11p, V2V, V2I

1. INTRODUCTION

With the increasing demand for traffic safety and efficiency and constant search for innovative solutions within the automotive market coupled with supporting initiatives from regulatory (governmental) domains, the potential of Intelligent Transportation Systems (ITS) is immense. Vehicle and roadside infrastructure connectivity and cooperation can be considered a future killer application for mobile networking technologies while also adding extra value to the car industry and network operator services. Such systems are suitable for a diverse spectrum of applications, including security, traffic and fleet control, and entertainment. The European Commission, through programmes like the i2010 Intelligent Car initiative, are driving the rollout of intelligent vehicle systems in both European and international markets by supporting ICT research and development in the area of transportation. Communications is the nervous system of ITS. Bodies including the Institute of Electrical and Electronic Engineers (IEEE), International Standards Organisation (ISO) and Car-to-Car Communications Consortium (C2CCC) are working on proposals for a communication solution to facilitate the envisaged ITS operational capabilities. The IEEE 802.11p protocol, also known as Wireless Access in Vehicular Environments (WAVE), will provide dedicated short range communications between vehicles or vehicle and roadside infrastructure and is regarded as the predominant technology to facilitate this interaction. The deployment of WAVE alone however will not meet all ITS expectations when considering the diverse range of value added services projected by various industrial players, including the C2CCC and ETSI [1, 2, 3]. Considering this, the ISO propose CALM, a Continuous Air Interface for Long to Medium range, as a complete high speed ITS communication solution using a heterogeneous mix of new and existing complementary media, ensuring continuous network connectivity; both vehicles and roadside units (RSU) can now have more than one communications medium option.

Prior to commercial deployment of any new technology, rigorous testing must be performed. In communication and computer network research, simulation is the most practical method of evaluation, allowing engineers to test scenarios that

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might be difficult or expensive to emulate using real hardware and designers to test new protocols or changes to existing protocols in a controlled and reproducible environment. Currently, since neither ITS infrastructure nor communications capabilities exist in vehicles beyond small scale prototypes, computer simulation is the only viable option in evaluation of potential ITS solutions. The challenge of simulating the vehicular network has multiple dimensions however; vehicle mobility is no longer completely random. The wireless channel behaviour is dependent on the driving scenario. Applications demand service using previously non-existent requirement parameters. This paper presents CALMnet, a comprehensive network-centric simulation environment for CALM-based cooperative vehicular systems. Using the OPNET modeler simulation tool, a number of elements necessary for accurate emulation of the complex cooperative vehicular network are identified and addressed. Important areas of consideration include vehicle mobility, communications channel behaviour, application structure and RSU and OBU device modelling to accurately represent the envisaged ITS concept.

The rest of this article is structured as follows. Section 2 conducts a review of the different approaches to simulation of vehicular network environments and examines various tools that are available to achieve this. A detailed description of the CALM standard, its fundamental role in the success of ITS and the steps taken in creating a simulation model is presented in Section 3. Section 4 introduces the IEEE802.11p standard and describes how it facilitates V2V and V2I communication. CALMnet is presented in Section 5, which outlines the modelling approach and implementation of application, mobility and channel components and finally, the conclusions and future work are presented in Section 6.

2. Related Work

Due to resource, safety and feasibility constraints, testing proposed ITS solutions is fundamentally reliant on computer simulation. There exist many network simulators, including ns2 [4], OPNET [5], QUALNET [6], GlomoSim [7] and SWANS [8], which allow researchers to evaluate proposed applications and protocols under different operating conditions. These network simulators provide reliable models of well known communication layer protocols for numerous types of network technologies, however none yet offer a complete, standalone ITS simulation solution. Many studies have proposed extensions to these well established network simulators or simply developed competing tools to address requirements specific to the accurate simulation of vehicular environments.

The predominant feature of ITS simulation is the representation of vehicle mobility. A number of studies propose vehicle network simulation solutions where accurate mobility modelling is the primary concern. Analysing the characteristics of these simulation environments, there exist two design categories based on the specific aspects of the system being studied. Application-centric simulation is used to evaluate the effect of ITS application deployment on driver behaviour. Conversely, a network-centric approach is required when examining the effectiveness of communication protocols in a vehicular environment.

Many proposed simulation solutions link a traffic simulation tool (e.g. SUMO [9], VISSIM [10]) with a network simulator; the traffic simulator produces realistic mobility patterns which are transferred to the network simulator mobility modelling process. Examples of such combinations include CORSIM/QualNet, VISSIM/ns2 [11], SUMO/ns2 [12,13,14], CARISMA/ns2 [15], STRAW/JiST [16] and VISSIM/QualNet [17]. Of these, the network–centric simulation tools [12,13,16] use the traffic simulator to generate mobility trace data files which act as an input to the mobility modelling process of the network simulator. The application-centric approaches [11,12,14,15,17] link both simulators in real time; over a TCP connection, the traffic and network simulators share information allowing the network simulator to query the current position of each vehicle and also dictate any driver behavioural actions that will impact vehicle mobility. While application-centric simulation models the effect of application data on driver behaviour and facilitates dynamic changes to vehicle mobility, this comes at the price of higher overhead and slowed simulation run time since both simulation tools must be synchronised. This overhead is without purpose for studies not concerned with affect of driver behaviour; network-centric simulation is better suited for such investigations.

The absence of a defacto simulation tool for ITS environments has prompted some to implement a standalone, specific purpose tool in its entirety [18,19,20]. Created specifically for simulation of vehicular networking environments, NCTUns, AutoMesh and GrooveNet demonstrate varying approaches to ITS simulation. While AutoMesh implements a flexible framework where various mobility, driver behaviour, network and propagation models can be plugged in, GrooveNet is primarily developed as a test-bed tool which enables real and simulated vehicles to communicate during on-road experiments. The NCTUns simulator, implemented using agent technology, combines vehicle mobility and communication protocols using the Linux kernel transport and network layer protocol suites.

With the exception of [19,20], all studies examined concentrate solely on the assurance of realistic mobility patterns in isolation with no consideration afforded for other aspects such as channel behaviour, application modelling and the CALM concept of "always on" connectivity. In fact, to date, no ITS-related simulation tool has implemented the CALM vision of multi-mode devices with heterogeneous communication technologies for ubiquitous coverage, and management of these, for sufficient ITS service support. The remainder of this article addresses this void, introducing CALMnet, a simulation environment dedicated for the ITS scenario as envisaged by the ISO CALM standard. The following section presents an overview of this task group's vision and proposed system operation.

3. ISO CALM

The primary objective of ITS is the creation of advanced road traffic systems for improved traffic safety, efficiency, and travelling comfort. The communications technologies used in ITS will play a vital role in the efficiency and effectiveness of such applications and is considered a primary concern in all ITS projects. Continuous or quasi-continuous communication among vehicles and between vehicles and roadside infrastructure is vital; the CALM initiative is designed to address this requirement [21].

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Projects such as CVIS [22], COOPERS [23] and SAFESPOT [24] and bodies including the C2CCC all endorse the CALM concept of a heterogeneous cooperative communications framework to provide user transparent, continuous communication in support of emerging ITS applications in the public transport, urban, interurban and freight and fleet domains. Part of the ISO Standardisation Program (ISO CALM TC 204), CALM combines complementary media allowing vehicles to use the best combination of the communications technologies that are locally available at any one time. The inclusion of multiple technologies in one communications solution requires some form of standardisation however; the provision of user transparent, seamless connectivity in such an environment necessitates a recognised convergence management approach. This is the role of the ISO TC204 WG16.

CALM defines a Management Entity (CME) which enables a flexible, adaptable and extensible communications system. Vehicles and RSUs can utilise all or a subset of the technologies and its modular design ensures that future new communication technologies can be integrated easily (Figure 1). The CME acts as the interface between the ITS applications and underlying communications media. Within the CME, three managerial bodies are defined:

- CALM Interface Manager: determines and records the status of each communication interface (CI) at any given time. Also reports to the CALM manager on the channel quality of each available medium.
- CALM Network Manger: responsible for performing the handover process enabling migration of application sessions to alternative media as dictated by the CALM manager.
- CALM/Application Manager: ultimately responsible for ensuring application transmission requirements are met. Interacts with interface manager to determine most suitable medium and instructs network manager to establish a connection.

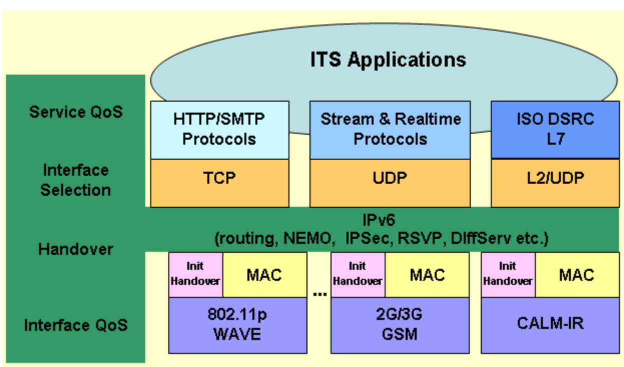

Figure 1: CALM Architecture

The communication technologies envisaged to support cooperative vehicular systems currently include WiFi and Wimax for regional connectivity, cellular systems such as GSM and UMTS for terrestrial coverage, as well as satellite and broadcasting communication technologies. Ad-hoc communication standards such as IEEE802.11p WAVE, InfraRed and MM-Wave will permit short to medium range communications between vehicles, Figure 2. CALM also proposes a non-IP CALM-FAST mode. This is offered with respect to time-critical safety applications and enables rapid transmission of short messages. While CALM is designed to support all media, there is no such requirement on vendors to roll out equipment with physical interfaces for all listed technologies. In fact, it is envisaged that different classes of vehicle/RSU will support different technology sets.

Many of the communications options cited in the CALM handbook are long existing and well established technologies with the exception of those identified for V2V interaction. Of these, the 802.11p WAVE standard is seen as the predominant means of enabling V2V communications and should therefore be an integral part of any ITS simulation environment. A brief description of WAVE and details of its operation are outlined in the next section.

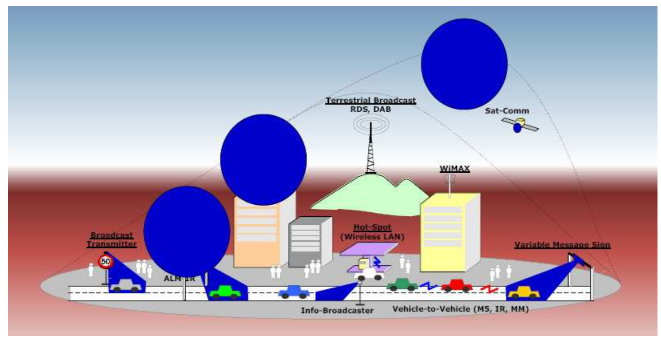

Figure 2: CALM multiple media environment

4. IEEE 802.11p WAVE

In 1999, the U.S. Federal Communications Commission (FCC) and later the European Telecommunications Standards Institute (ETSI) in 2005, approved a frequency band reservation in the 5.9 GHz (in Europe 5 GHz) band for wireless communications between vehicles and roadside infrastructure. At present the Institute of Electrical and Electronics Engineers (IEEE) is completing the final draft of the IEEE P1609 "Standard for Wireless Access in Vehicular Environments (WAVE)". Due to the success of IEEE 802.11 in the area of data communication, it presupposes that this standard will be one of the main wireless technologies implemented in vehicular network, more specifically 802.11p which is defined by an IEEE working group. In the draft WAVE specification seven channels each of 10MHz bandwidth are defined in which one of them, called the Control CHannel (CCH) is reserved for management frames and emergency messages, while the six Service CHannels (SCH) are used for data frames interchange. Channel coordination relies on a synchronisation procedure and is required to support data exchanges between one or more devices that are not capable of simultaneously monitoring the CCH and exchanging data on SCHs. Such devices are herein termed single-channel WAVE devices. All WAVE devices monitor the CCH during a common time interval termed the CCH interval. This interval allows for the sending of high priority WAVE Short Messages (WSMs) or WAVE Service Advertisements (WSAs). The default values for CCH and SCH intervals specified in WAVE standard are 50ms. During the CCH interval, every node has to monitor the CCH, and during the SCH interval, nodes may switch to a SCH for transmission or reception. At the beginning of each scheduled channel interval, a guard interval is be used to account for

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variations in the channel interval time and timing inaccuracies among different devices. Transmission shall not be permitted during the guard interval.

The CCH time slot (CCH TS) supports WSA and WSM transmission and reception. The WSAs are beacon frames broadcasted over 1-hop every 100ms, announcing the use of a SCH. These beacons are of particular importance for VANET communications, since many safety applications, including the WAVE Short Message Protocol (WSMP), are reliant on them. The WSMP is defined in the WAVE Standard as a non-IP communication protocol designed for optimised operation in the WAVE environment and based on a WSM interchange directly between WAVE devices. All the high priority WSMs are sent and received through the CCH, with the consequent advantage being the use of the optimised operation and high priority access provided for this channel. The WSMs are designed to consume minimal channel capacity and allow applications to directly control physical layer characteristics, e.g., channel number and transmitter power. A transmitting application also provides the MAC address of the destination device, including the possibility of a broadcast address. WSMs are delivered to the correct application at a destination based on the Provider Service Identifier (PSID). The major advantages of this protocol are that WSMs can avoid the overhead associated with IP data exchange or the management overhead associated with initiating a WBSS, and use the optimised operation and high priority CCH access.

The IEEE P1609 "Standard for Wireless Access in Vehicular Environments (WAVE)" is split into four sub-standards where IEEE P1609.1 defines the WAVE management activities, IEEE P1609.2 [25] relates to the security protocol, IEEE P1609.3 [26] defines the routing and transport services and lastly the IEEE P1609.4 [27] defines the multi-channel operation. The physical layer is based on the IEEE 802.11p PHY, which is a variant of the IEEE 802.11a PHY and uses the OFDM modulation scheme, providing for longer ranges of operation (up to 1000 meters) in high speed environments (up to 500km/h relative velocities). The MAC layer is derived from the IEEE 802.11e standard and is described in IEEE P1609.4. The main modification as regards the IEEE 802.11e is the extension to multichannel operation. The LLC layer is specified in the IEEE 802.2 Standard, and two different communication protocols are available for the applications: IPv6, and WSMP. In the Management part of the WAVE protocol stack, PHY Layer Management Entity (PLME), MAC Layer Management Entity (MLME) and finally the WAVE Management Entity (WME) define the different transactions between the layers and sublayers.

WAVE is just one of the required considerations in a comprehensive CALM-based simulation solution. The next section introduces CALMnet, detailing all of its constituent modules and the design and modelling approaches taken in their implementation.

5. CALMnet

This paper presents CALMnet, a CALM-compliant simulation environment for ITS research and experimentation. Developed using the OPNET modeller simulation tool [5], the CALM architecture shown in Figure 1 has been developed. A network-centric simulation approach, the primary usage of CALMnet lies in the examination and extension to the communication protocols, procedures and management processes. This requires modelling on a number of levels; CALM nodes must be constructed, potential application sets must be identified and implemented and a number of environmental factors including vehicle movement and channel behaviour must be considered.

The design and architectural description of these components are presented in the remainder of this section.

5.1 CALMnet Device Architecture

CALM facilitates both V2V and V2I communication modes and therefore it is important to differentiate between the vehicle On-Board Unit (OBU) and RoadSide Unit (RSU) devices. Currently, CALMnet implements both vehicle and roadside device models which use a subset of the complementary radio technologies identified in the CALM specification. Since both have differing requirements and functionalities, CALMnet implements OBU and RSU nodes, the features and implementation details of which are outlined in the following subsections.

5.1.1 Vehicle OBU Device

The fundamental purpose of ITS is to enable vehicle and infrastructure collaboration with the goal of improving modern transportation. To achieve this, vehicles must have the capability to communicate with each other and also require a connection to the infrastructure. This vehicle-to-infrastructure communication can take place directly or via roadside unit devices. The communications interfaces developed for the multimode vehicle OBUs as part of this work includes UMTS and IEEE802.11p WAVE wireless protocols. This offers a comprehensive CALM communications solution; the wide scale availability of UMTS provides an "always on" feature, facilitating direct connection to the wired network infrastructure. Alternatively, WAVE empowers vehicle-to-vehicle and vehicle-to-roadside communications providing higher speed, regional and local coverage. The architecture of each simulated vehicle OBU is illustrated in Figure 3.

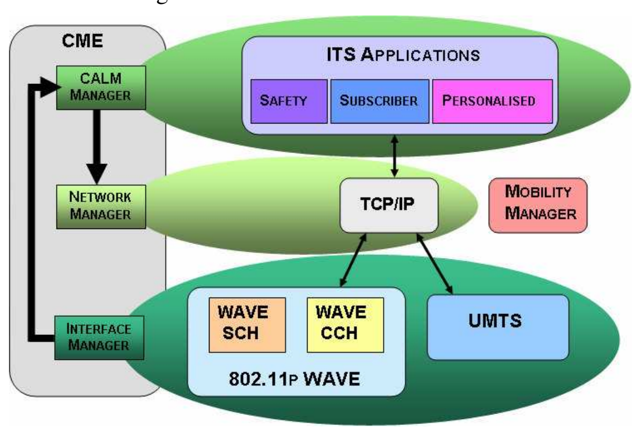

Figure 3: CALMnet Vehicle OBU device architecture

The OBU comprises a number of components which form three basic modules. Vehicles will run any number of ITS services. These interface with the CALM manager, indicating the required operational constraints before sending data to lower networking layers. In the vehicle OBU, three CIs are available for data

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transmission; the WAVE module provides both a Control CHannel and Service CHannel, while dissemination over a UMTS connection is also possible. Results of performance diagnostics carried out on each CI are recorded by the interface manager and reported to the CALM manager which determines the most adequate CI. The Network manager interfaces with the TCP/IP process which performs addressing and routing functions. The mobility manager handles the movement of the vehicle and acts as the GPS receiver; all other processes can access current positional information from this component directly.

5.1.2 Roadside Unit Device

RSUs can act as gateways to the infrastructure-based control centres and are localised data stores for regional information. The simulated RSU device architecture is presented in Figure 4. Note the differences between this and the vehicle OBU structure. Since RSUs are stationary objects placed intermittently along roadways, no mobility management process is required. Also, note that the RSU node model has four CIs. WAVE CCH and SCH permit connectivity with passing vehicles, while both a UMTS and wired 802.3 communication option are provided. This facilitates two RSU configurations in CALMnet which are denoted as primary and secondary RSUs. Primary RSUs have a wired connection to the network backbone where the Traffic Control Centres (TCC) and application provision servers are hosted, while secondary RSUs use a UMTS connection to gain access to the wired network. Since the cost of installing primary RSUs at every cited location is prohibitive, only a small percentage of these will be deployed. Secondary RSUs can be deployed to supplement the services provided by their primary counterparts.

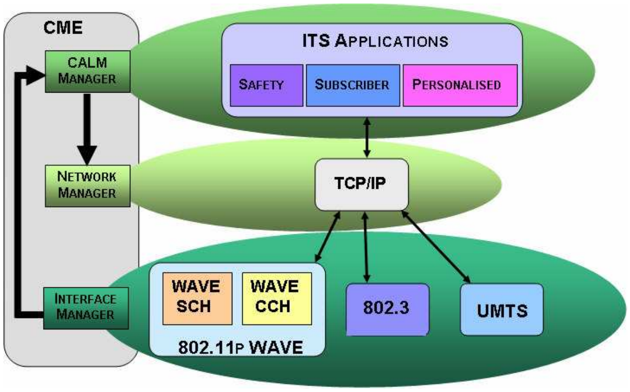

Figure 4: CALMnet RSU device architecture

5.2 WAVE Modelling

Since these are well known and long established technologies, the UMTS and 802.3 modules are standard models provided with the OPNET modeller simulation tool. The WAVE specification however is not currently realised. CALMnet resolves this issue, providing a working WAVE simulation model based on the IEEE802.11p specification.

In the current WAVE implementation, each multi-channel unit supports one CCH and multiple SCHs. The WSMP [26] protocol is implemented on the CCH to process WSA messages which are periodically transmitted every 0.1s; safety-related messages based on the WSM format are also transmitted on the CCH. The CCH and SCH TimeSlot intervals (CCH TS, SCH TS) are both 50ms in duration and the beginning of each channel timeslot is marked by a guard time of 5ms. Time slots are synchronised with OPNET global simulation time to approximate GPS synchronization. WSA and WSM messages are transmitted strictly in CCH TS over CCH interface. IP data packets are transmitted over SCH interface.

The following subsections discuss WAVE simulation model implementation at different layers of the OPNET node model.

5.2.1 Physical Layer

WAVE units operate on simplified 802.11p standard which is an extension of the pre-existing 802.11a model provided in OPNET. In current implementation, 5.9GHz band is used with 7 channels (1xCCH, 6xSCH) of width 10 MHz. The data rate is set at 6 Mbit/s and the OFDM modulation scheme is configured.

5.2.2 Link Layer

The Link layer according to the WAVE standard is called the WAVE MAC. The WAVE MAC is based on the IEEE 802.11e standard and allows service differentiation using data classification priorities. The WAVE MAC uses the 802.11e-based channel coordination function for each of node's network interface. In our implementation we extend the 802.11e MAC to support synchronisation of the CCH and SCH timeslot intervals; this ensures that all data (WSMP or IPv4) is transmitted in the correct time slots (CCH TS, SCH TS) and over the correct interface (CCH, SCH).

5.2.3 Higher Layer

Both WAVE and CALM standards specify the use of IPv6 at the communications network layer. In our implementation, the simpler IPv4 protocol is currently used for data communication over the SCH. Also, a simplified WSMP protocol is implemented for transmission over the CCH. Here, both beaconing and safety-related message types are supported based on the WSA and WSM formats.

Table 1 summarises the current implementation of WAVE in the OPNET simulator.

5.3 Application Modelling

Vehicular applications are of primary importance in ITS; they provide the functionality to improve future road safety, efficiency and traveller comfort and are supported by the underlying communications technologies. Within CVIS for example, envisaged applications include an enhanced driver awareness service (EDA) which keeps drivers informed of current local road and traffic conditions, and a cooperative traveller assistance service (CTA), which provides pre- and on-trip route planning support. A number of traffic planning, control and management services are also proposed. A number of safety services ranging from intersection safety to pre-crash protection are proposed by PReVENT [28], while VII [29] is working on systems for congestion relief and collision prevention. In addition to these applications, the European Telecommunications Standards Institute (ETSI) have outlined a number of safety and non-safety services for the intelligent transportation sector [2,3].

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Table 1: Parameters of implemented WAVE in OPNET

Protocol	WAVE	WAVE in OPNET
Type of nodes		
Single Channel unit	yes	no
Multichannel unit w/o time synchronization	yes	no
Multichannel unit w/ time synchronization	yes	yes
Type of network interface		
OBU	802.11p/WAVE	802.11p/WAVE
RSU	Not specified	802.11p/WAVE UMTS, 802.3
Physical layer		
Standard	802.11p	802.11a
Band	5.9 GHz	
Bandwidth of channel	10 MHz	
Data rate	6Mbit/s	
Channels	1xCCH, 6xSCH	
Link layer		
Protocol	WAVE MAC	802.11e MAC w/ Channel Coordination
QoS	yes	yes
Timeslots	yes	yes
Network layer		
Network protocol	WSMP, IPv6	WSMP, IPv4
Safety-related messages	WSM (368 b)	WSM (368 b)
Beacon messages	WSA (416 b)	WSA (480 b)
Beaconing interval	100 ms	100 ms

CALMnet allows users to configure a broad range of upperlayer applications, each with differing operational requirements and priorities. Three service classes are defined, taking the potential application sets in the ITS space into consideration. These are:

- Safety Services

  This category encompasses a variety of critical applications necessary to enhance travelling safety. Informing the driver of collisions, road hazards, dangerous driving conditions and emergency vehicle approach is the chief responsibility of applications in this category.

- Subscriber Services

  This includes a number of commercial and informational services to which a traveller can subscribe. Drivers may wish to receive information regarding the traffic state on their chosen route to a particular destination, for example. Commercial advertising and in-vehicle multimedia streaming are also envisaged as subscriber based services where travellers express interest in receiving certain information. This category comprises of an infrastructure push based model where the roadside infrastructure delivers data to subscribed users.

- Personalised Services

  This category encompasses applications which cater for individual traveller requirements. Route planning and updating activities will be unique for every vehicle for example, and so will fit into this class. Transaction based applications such as parking space reservation and temporary bus lane usage also fall into the category of personalised services.

These are generic categories within which individual application specifications can be defined. This flexible approach ensures that any proposed ITS service can easily be modelled and tested in the CALMnet simulation environment. It also enables users to test the limits of both the system as a whole and the application design in relation to successful service operation in the ITS scenario.

5.4 Mobility Modelling

As highlighted in many other studies, the accurate modelling of vehicle mobility is a fundamental task for ITS simulation. CALMnet uses a network-centric approach whereby the offline trace files generated by an external mobility package serve as the input for the simulation mobility process. This network-centric approach to mobility modelling also enables CALMnet flexibility; the system can easily work with any chosen traffic simulator.

The open source Simulation of Urban MObility (SUMO) package has been selected as the road traffic simulator employed to generate realistic microscopic vehicular mobility patterns. SUMO allows high performance simulations of huge networks with roads consisting of multiple lanes, as well as of intra-junction traffic on these roads, either using simple right-of-way rules or traffic lights. Vehicle types are freely configurable with each vehicle following statically assigned routes, dynamically generated routes, or driving according to a configured timetable.

SUMO supports maps from NavTech-Files stored in the ArcView database format, maps from other simulation suppliers such as PTV (VISSIM, VISUM), TIGER maps and can also import road networks from OpenStreetMap (OSM) [30]. OpenStreetMap is a project whose aim is to create and provide free geographic data such as street maps to anyone who wants them. The maps are created using data from portable GPS devices, aerial photography, local knowledge or other free sources and contain a rich information set which is used by SUMO in configuring the simulated road network and therefore dictating vehicle mobility rules. Such information includes the presence of traffic lights, the number of lanes present, the type of street, (e.g. pedestrian, highway etc), local speed limits etc. An example of a configured road topology is illustrated in Figure 5.

A powerful tool for realistic mobility simulation, SUMO allows complete configuration flexibility. Multiple vehicle classes with diverse characteristics can be defined to follow different pre-defined or random routes and realistic driver behaviour representation is inherent. As shown in Figure 6, vehicles obey traffic signals, can change lanes and perform overtaking. Likewise, lanes can be restricted to allow only certain traffic types, e.g. bus lanes etc, enabling realistic simulation of vehicle movement in the simulated scenario. During SUMO simulation runs, each vehicles mobility trace data is logged and filed offline. These generated trace files are imported to the OPNET CALMnet environment where the mobility manager model handles vehicle movement. Here, position updates happen on demand; each vehicle's current position is calculated only when such information is required, minimising the models reliance on interrupt mechanisms and therefore resulting in more efficient simulation runs.

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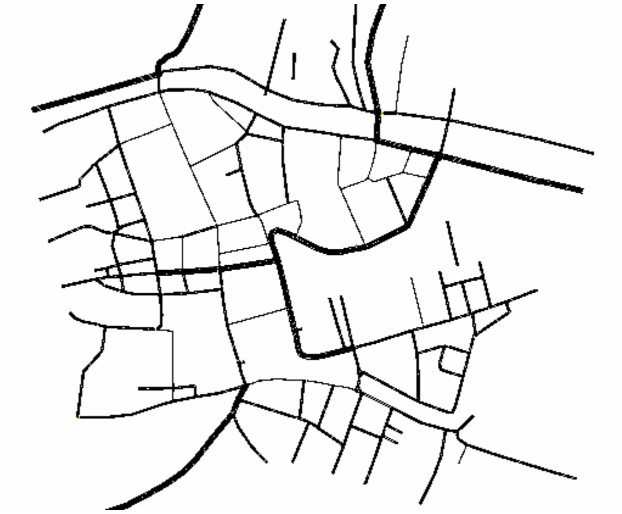

Figure 5: SUMO road topology

(a)

(b)

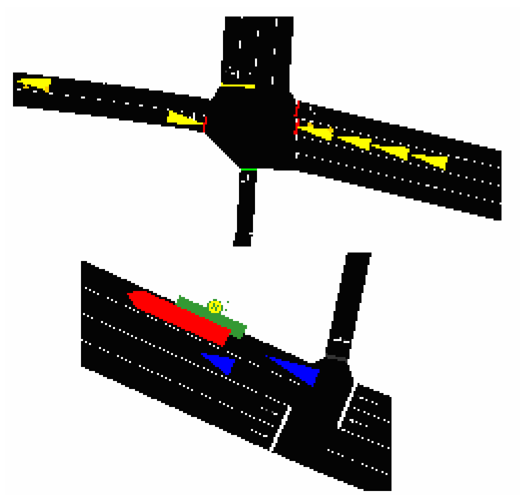

Figure 6: Using information provided by the OSM, SUMO derives basic driver behavioural rules. (a): vehicles waiting at red state traffic lights. (b): vehicles overtake a stopped bus

5.5 Channel Modelling

Typically, wireless network simulators assume a generic propagation model, such as *Free Space* model or *Two-Ray Ground* reflection model coupled with a Shadowing model [31]. Naturally, such a generic model may not be appropriate for the propagation environment to be evaluated. Furthermore, parameters of such models (e.g., pathloss exponents) still need to be instantiated. In the case of wireless vehicular communications, results obtained based on simulations have often been questioned [32,33], primarily due to the lack of realistic lower layer models. Research in the use of wireless vehicular communications for ITS applications requires high accuracy to ensure that the achieved results closely match those that could be obtained under real operating conditions. The V2V propagation channel has strong impact on the coverage, reliability, and real-time capabilities of V2V ITS applications. Theoretical models for the V2V channel have been discussed by a number of authors [34,35,36,37,38,39,40]. However, real driving environments do not always adequately satisfy the assumptions made in these models and can lead to erroneous conclusions on the effectiveness of some proposed ITS services, as shown in [41].

One of the main objectives of CALMnet is to accurately model the propagation behaviour using an empirical measurement-based approach for different vehicular environment scenarios. Using 802.11p-enabled prototype OBUs developed as part of the CVIS project, measurements were performed between two vehicles travelling at various speeds and distances in different scenarios. Since channel characteristics differ in diverse environments, measurements were gathered in three distinct driving categories.

- *Motorway*
  With between 2 and 4 lanes in each direction and few or no surrounding structures, vehicles travel up to 120kmph.
- *Rural*
  Quiet, narrow roads with one lane in each direction; few buildings, numerous trees and hills. Speeds here vary between 50 and 80kmph.
- *Urban*
  Dense traffic scenario with between 1 and 2 lanes in each direction; many junctions and traffic lights resulting in intermittent driving periods with maximum speeds at 50kmph. Surrounded by high buildings.

Each test lasted at least one hour with one car acting as transmitter and the other as receiver, and different relative speeds, inter-vehicle distances, traffic conditions in both LOS and NLOS communication states. During each test scenario, the vehicle acting as transmitter sent an ICMP request every 100ms to the second vehicle. A complete data set of RSSI values is often not available due to the fact that RSS values are only recorded when the corresponding packets are received successfully, resulting in potential bias in parameter estimation [15]. To minimize the bias introduced by such dropped packets in our empirical data set, we only use data samples in those particular distance bins which have a packet delivery ratio above a certain threshold, which is set to 70% in this case. For each packet successfully received, the RSSI value is recorded where RSSI is in dbm above the noise floor and is measured during the preamble and PLCP portion of the received frame. GPS-based location, velocity, and timestamp information is logged periodically. Fading analysis can be conducted by modelling the dependence between logged RSSI values and relative distance of communicating vehicles in the different scenarios. The parameters of the different models can then be estimated using the empirical data from the measurement campaigns.

For packet throughput the total number of packets sent and received is recorded over 10m bin intervals. The restrictions imposed by the environment where the tests were done impact the measurements captured (in terms of inter-vehicle distance, influence of surrounding vehicles/buildings/trees and traffic signals). In the motorway and rural scenarios for distances of up to 80-100m the packet delivery threshold of 70% was satisfied i.e. a packet loss ratio of 30% or less was achieved. While successful communications beyond these distances (up to 200m for the motorway and 140m for the rural environment) is possible, for our test campaign the majority of the readings were captured within this range and beyond this the packet delivery

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http://dx.doi.org/10.4108/ICST.SIMUTOOLS2010.8694

ratio falls below the required packet delivery ratio of 70%.. For the 3 scenarios presented the packet delivery ratio threshold of 70% was approximately satisfied up to a distance of 80m for the motorway and rural environments and up to a distance of 40m for the urban scenario. Consequently the RSSI measurements are truncated at 80m for motorway and rural scenarios while for urban the cut-off point is 40m.

There are three main factors that play a role in determining the received signal power: pathloss, shadowing and multipath fading. Following the modelling approaches presented in [42, 43, 44] and using our empirical measurements a simple channel model for simulation of large-scale VANETs based on the CVIS communications platform in urban, rural or motorway environments is developed and the matching is presented in Figure 7. As the Line-Of-Sight (LOS) component is dominant in V2V channels the fading is dominated by Multipath Fading with little to no shadowing. To model the multipath reception of scattered signals *Nakagami*, *Rician*, and *Rayleigh* distributions are typically used and dependent on the density of the scattered signals, the total received signal can show different fading characteristics [42, 44]. The general nature of the Nakagami distribution is able to model Rician and Rayleigh fading [44] and is used in our model. Figure 7 illustrates the theoretical model matching representation of the empirical data (in blue) captured for the motorway environment. Note that here the proposed Nakagami model includes attenuation due to distance coupled with multipath fading components. From this plot, it is evident that the Nakagami matched model can accurately match the empirical measurements (as was the case for the rural and urban environments). Consequently, for the varied driving environments, CALMnet uses the Nakagami distribution based model as the basis for our computer simulation model development. Detailed explanation of the estimated parameters and description of the estimation process can be found in [45].

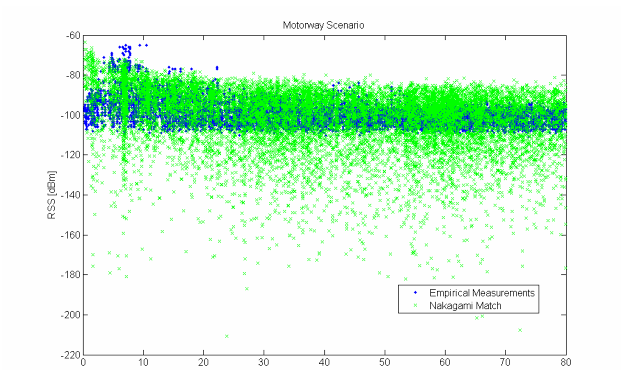

Figure 7: model matching for motorway scenario

5.6 CALMnet Simulation Case Study

As previously mentioned, CALMnet has been developed on top of the OPNET simulation tool. OPNET Modeler is an object oriented simulation tool with a hierarchical model structure. Using a finite state machine for discrete event simulation, Modeler provides a large range of inbuilt protocol and vendor device models for analysis of communication networks, protocols and applications. Since CALMnet is modular in design, its associated models can easily be incorporated in other simulation tools such as Ns, OMNET, and Glomosim however.

This section presents a simple case study highlighting CALMnet simulation set up and performance.

5.6.1 CALMnet SetupProcedure

Run over the OPNET modeller tool, CALMnet is a dedicated simulation environment for the ITS scenario. The first to fully model the CALM-based vehicular setting, it is capable of supporting high density networks with hundreds of nodes. The simulation configuration procedure is a tri-phase process, as illustrated in Figure 8. Stage one involves decisions associated with the physical environment to be modelled; the type of driving scenario (rural, urban, highway) and associated parameters (e.g. size dimensions) must be quantified. Once these physical environment parameters have been finalised, the cartographic description of the chosen physical environment is imported to the traffic simulator for phase two. Using this map the traffic simulator builds a road network for mobility simulation. At this point features such as the required vehicle density, types of vehicle to simulate and the characteristics of each, as well as the vehicle route calculation are considered. The final phase of simulation configuration takes place in the CALMnet OPNET based environment. Here, both the pre-existing and newly developed models are used to create a simulated scenario that is closely matched to the envisaged reality. This involves a number of configuration tasks. CALMnet OBU and RSU nodes must be deployed. WAVE model options such as transmit power, data rate etc, can be set. It is also possible to choose a channel model to accurately capture characteristics for each CI. Another aspect of system setup which must be considered is the design of the system infrastructure; UMTS components including the NodeBs, RNCs, SGSN and GGSN must be deployed. Also, application servers and traffic control centres are hosted in this section of the network. The final configuration activity involves specification of the applications that will run in the simulated environment.

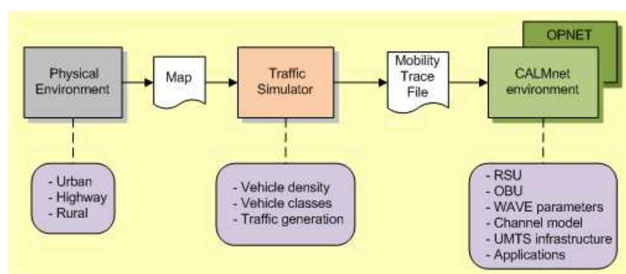

Figure 8: Triphase CALMnet setup process

To minimise the simulation configuration time overhead, CALMnet provides a base scenario which contains a fully deployed infrastructure network; all CALMnet models are also configured with default settings most appropriate for the ITS environment (e.g. relevant channel models etc). This reduces the main CALMnet configuration tasks to the application specification and RSU placement and primary/secondary RSU deployment ratio determination.

The following sections detail a simple V2V simulation scenario setup designed to analyse basic CALMnet performance at differing vehicular network densities.

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http://dx.doi.org/10.4108/ICST.SIMUTOOLS2010.8694

5.6.2 Simulation Scenario

An important task when establishing the baseline performance of any simulation tool is to design the reference scenario; for CALMnet, a standard V2V communication paradigm is chosen to indicate the reference simulation behaviour. This acts as a benchmark performance indicator of CALMnet for simulation of a vehicular networking environment.

The V2V network is modelled is a highway scenario that is represented by 3 lanes in each direction with a length of 2km. The traffic model contains dynamically moving vehicles in each lane with varying speeds that are restricted to a maximum of 120km/h. In this reference scenario the only data traffic is in the form of beacon frames, transmitted every 100ms on the WAVE CCH in every vehicle; no application traffic introduced ensuring the simulation results reflect CALMnet baseline performance. Simulation runs of 10 seconds were carried out for node densities ranging from 100-500 vehicles, representing free flowing to congested traffic states. A synopsis of the base scenario settings are presented in Table 2.

Table 2: Simulation Scenario Settings

Simulation Parameters	Values
Transmit power	18 dBm
Frequency	5.9 GHz
Data rate	6 Mbit/s
Bandwidth of channel	10 MHz
Transmit range	Empirical model
Speed of vehicles	0-120 km/h
Scenario Dimensions	2 km, 3 lanes in 2 directions
Density of nodes/km	200-500
Size of beacons	480b
Beaconing interval	100 ms

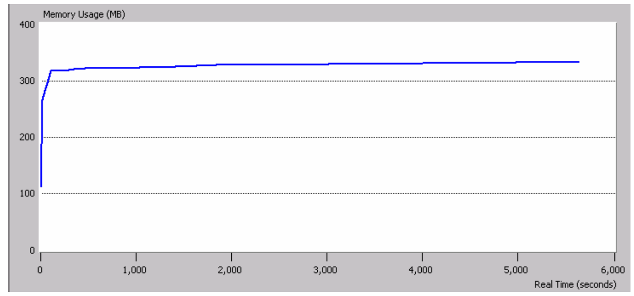
5.6.3 CALMnet Performance

Simulations were run on a Microsoft Windows Server 2003 machine with a VMWare virtual machine running Windows 2000 running at 2GHz. Figure 9 presents the measured performance of CALMnet in terms of memory consumption and execution speeds when 500 vehicles are simulated. After the initial settling down period, the memory usage stabilises at approximately 330MB as the simulation speed gradually decreases to below 20,000events/second. The performance observed for all other vehicle densities show similar trends, the results of which are presented in Table 3 for comparison. As expected, the number of simulated nodes has a major affect on the simulation run times and the amount of memory required.

Table 3: CALMnet benchmark performance at varying vehicle densities

Vehicle Density	Simulated Time	Simulation Duration (real time)	Memory Usage	Average Speed (events/sec)
100	10s	38s	38MB	107 846
200	10s	287s	80MB	56.391
300	10s	1630s	150MB	22.520
400	10s	3539s	225MB	18 370
500	10s	5652s	330MB	17 905

a) Memory Consumption



b) Simulation Speed (events/sec)

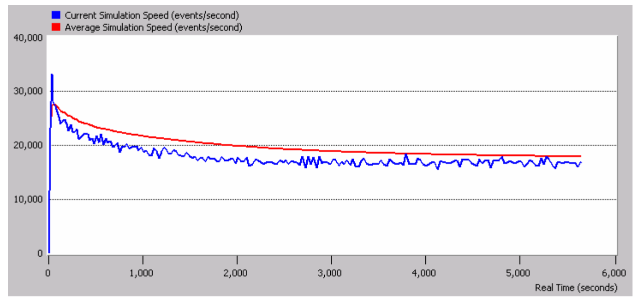


Figure 9: CALMnet performance for 500 nodes

6. CONCLUSIONS & FUTURE WORK

Due to resource, safety and feasibility constraints, testing proposed ITS solutions is fundamentally reliant on computer simulation. The majority of proposed ITS simulation solutions concentrate solely on the assurance of realistic mobility patterns in isolation with no consideration afforded for other aspects such as channel behaviour, application modelling and the CALM concept of "always on" connectivity. This paper presents CALMnet, a network-centric simulation model for CALM-based ITS systems using the OPNET modeler simulation tool. Considering vehicle mobility, channel behaviour, application characteristics and CALM management entities, a complete CALM simulation environment is implemented. Using a heterogeneous mix of complementary radio technologies, vehicles have continuous coverage, fostering a large set of potential services in the ITS domain.

CALMnet is a simulation tool primarily implemented for the examination of lower layer protocol performance in the CALM ITS environment. Accurate environmental modelling, therefore, is vital. Future work will focus on the characterisation of the V2I channel behaviour for more accurate modelling of this communication scenario. Further development of the OBU node model to incorporate additional communication interfaces to allow connectivity in WiFi hotspots and WiMax networks for example, is also planned. The use of IPv6 is an important consideration for vehicular networking and inclusion of this protocol is another intended extension to the current CALMnet version.

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