Performance Evaluation of Networking Protocols for Connected Vehicles

Andreas Pressas, Mümin Özpolat, Zhengguo Sheng, Falah Ali
Department of Engineering and Design, University of Sussex, UK
Email: a.pressas@sussex.ac.uk

Abstract

Modern cars feature many embedded systems that monitor and manage all the critical sensors and actuators. The interconnection of such systems is a challenging task since the information to be exchanged is of mission-critical nature and affects the driving experience. The vehicle connectivity can be further extended with Vehicle-to-Vehicle (V2V) technology, which allows cars to exchange sensory information and even act on it. In this article a unified networking architecture is presented, starting from the inside of the vehicle and the interconnection of various control units and ultimately targeting Car-to-Car communications which enable smarter, safer and more efficient transportation. The researchers review and evaluate the performance of Power Line Communications as a solution for in-car networking. Then the safety-critical data as well as multimedia originating from each individual vehicle's in-car network are broadcasted to other neighbouring vehicles via IEEE 802.11p in a simulation environment featuring realistic vehicular mobility. The authors examine the performance of the proposed solutions for both inter-car and intra-car networking in the context of safety-critical communications via computer simulations built with OMNeT++.

1 Introduction

The technological advances of the past few years in the field of vehicular communications, regarding both software and hardware, are enablers of new types of networks targeted for previously unexplored environments. The Connected Vehicle Network (CVN) is a network type that has received a lot of interest in the last few years from researchers, standardisation bodies and developers, since it has the potential to improve road safety, enhance traffic and travel efficiency as well as make transportation more convenient and comfortable for both drivers and passengers (I. Ku, 2014). It is envisaged to be a critical building block of the Internet-of-Vehicles (IoV), Intelligent Transport Services (ITS) and the Smart Cities concept.

CVNs are networks which allow the exchange of kinematic data among vehicles. They consist of collections of vehicles equipped with on-board units which offer wireless communication capabilities. They are considered a more practical case of Mobile Ad Hoc Networks (MANETs), with the key difference in the nodes' mobility patterns as well as data transmission and services initialized from in-vehicle networks. The nodes in MANETs can describe random trajectories, unlike CVNs in which the nodes are considered to move on predefined road networks. The topology in CVNs is still characterized by high dynamism, since the nodes/vehicles can transit on the roads with high speeds. This means that the wireless links between vehicles last a short time, and consequently that CVN applications need to disseminate data in a fast and efficient manner.

The evaluation of CVN protocols and applications can be done using real On-board units (OBUs) embedded on actual cars moving on a highway or an urban area (K.C.Lee, 2007), but there are issues with this approach since it is expensive and time-consuming. These issues, in addition to its inflexibility and the lack of compatible RF hardware (e.g., IEEE 802.11p) mean that there is a real need for accurate, realistic large scale simulations for in-vehicle, Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications in close to real life scenarios-particular for academic research.

This work provides an end-to-end solution for evaluating communication protocols for connected cars, starting from the inside of the car and ultimately targeting inter-vehicle communication. The network simulation is built using the OMNeT++ (A. Varga, 2008) simulation library, coupled with the SUMO (M. Behrisch, 2011) open traffic simulator. Specifically, the in-vehicle communications are based on a custom-built model of the HomePlug Green PHY (HPGP) and inter-vehicle communications is using IEEE 802.11p (IEEE, 2010) PHY and MAC models from the VEINS (C. Sommer, 2011) framework. Maps of the University of Sussex campus extracted from real-world data were used to approach realistic traffic conditions when conducting out V2V simulations.

In the following chapter the authors give a systemic view of the connected vehicles. The main body of work, presented on the following chapters is targeted towards modelling the networking that takes place both in the interior of the vehicle, as well as from Vehicle-to-Vehicle. Then by using this very simulation environment and some realistic traffic data the researchers evaluate

IEEE 802.11p for use in the Ad Hoc domain. The remainder of the paper is organised as follows; Section 2 describes a high-level system architecture for CVNs, Section 3 focuses on In-car communication technologies and Section 4 in Vehicle-to-Vehicle communications. Section 5 is focused on simulations and evaluation of proposed networking solutions. Finally, the last section concludes the presented work and identifies the future work to be done.

2 Architecture

The CVN system architecture comprises of three domains: the in-vehicle, the ad hoc and the infrastructure domain. Fig.1 illustrates the overall architecture of connected vehicle system.

1.1. In-Vehicle Domain

The in-vehicle domain is composed of one or multiple on-board units (OBU), Advanced Driver Assistance Systems (ADAS) sensors such as cameras, proximity sensors, engine sensors, radars and actuators such as brake and the steering wheel. The communication between these systems is usually wired, based on Controller Area Network (CAN) bus, Local Interconnect Network (LIN), as well as by Ethernet.

With the emerging automated tasks in vehicle domain, the development of in-vehicle communications is increasingly important and subjected to new applications. These applications of different network technologies and point-to-point links, however, lead to an inflexible network architecture and a complex cable harness in vehicles. In order to cope with next generation vehicle intelligence, vehicle manufactures are always on the lookout for simplified approaches of reducing complexity, weight and cost of material. Recent development of vehicular power line communications (VPLC) (Z. Sheng, 2016) is promising and entirely novel to in-vehicle applications.

1.2. Ad-Hoc Domain

Mission critical communications is a very challenging topic to deal with in CVNs, since the bandwidth is limited, the topology is highly mobile and there is a lack of central coordination. The ad hoc domain is composed of vehicles equipped with OBUs and Roadside Units (RSUs). An OBU can be seen as a mobile node in an ad hoc network and RSU is a static node. The communications for V2V and V2I are based on the Dedicated Short Range Communications (DSRC/802.11p) stack. In this domain, vehicles cooperate to deliver data messages through multihop paths, without the need of centralized administration. Most of the envisioned applications and services rely on the delivery of broadcast messages without infrastructure support. Consequently, reliable one-hop broadcasting, in which a packet from the source nodes is guaranteed to arrive in time to all nodes within the source node's transmission range is a fundamental component of CVNs.

1.3. Infrastructure Domain

The infrastructure domain refers to RSUs connected to the Internet via some gateway. The existence of these RSUs or other hotspots located outside of the road network is what makes the smart cities connected. The vehicles' OBUs may connect to the Internet through V2I communications. In the absence of RSUs or hotspots, OBUs can also communicate with each other and the Internet by using cellular radio networks (3G, 4G, LTE-V).

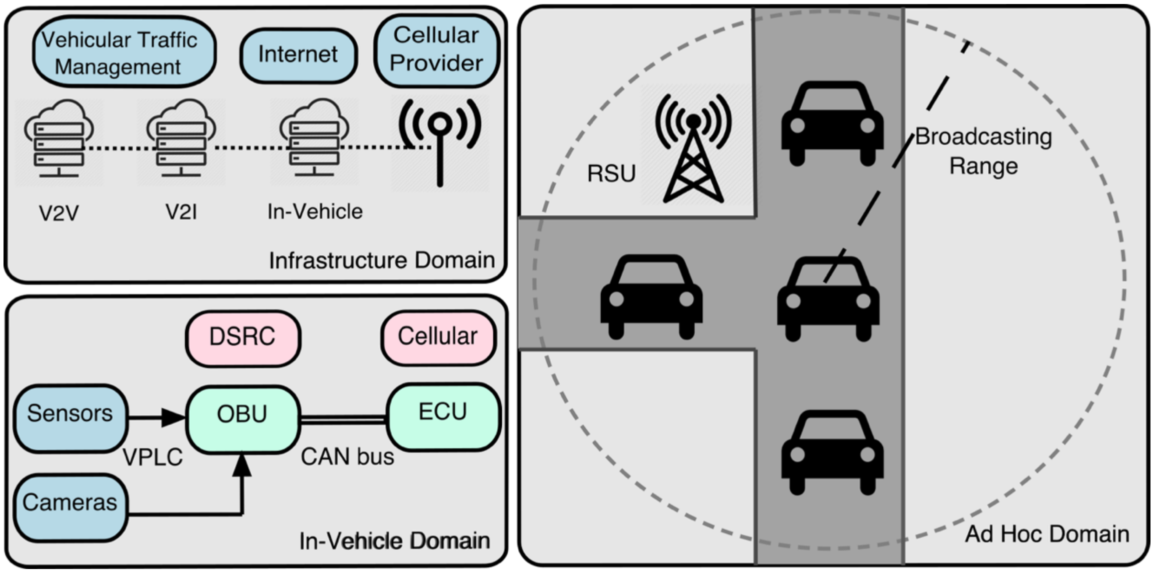

Figure 1: Connected Vehicles Architecture

3. In-vehicle Communication

The authors adopt an in-vehicle communication network from a real car service manual and regenerate it into Fig. 2 as the demonstration topology, where a total number of 16 nodes are connected via two buses to the dashboard. The communication bus is our proposed HPGP based VPLC, but can also be replaced by CAN or LIN, etc. Each node sends messages at a certain rate that is dependent on the selected priority value. According to real application requirements, those nodes are categorised into two classes: The high priority class includes all nodes with time-critical requirement, e.g., automotive sensors and actuators including engine, brake and wheel, whereas the low priority class includes nodes with non-stringent requirement, such as internal cockpit sensors including lighting, seat position and door locks.

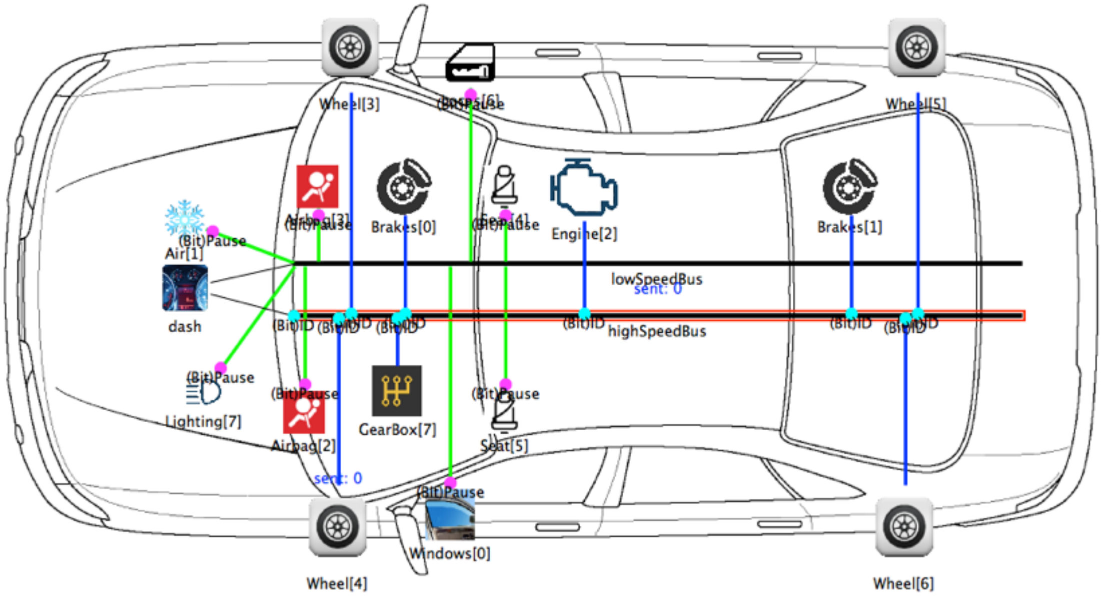

Figure 2: In-car communications in OMNeT++

Essentially, every ECU has several main wires, namely a power wire and at least one data wire. True power of PLC lies in that concept. Therefore, PLC technology enables us to transmit and receive data through power lines that gives us an opportunity to get rid of data lines. Removal of data lines from the all in-vehicle networks would provide significant decrease in the system complexity, maintenance cost, overall weight and fuel consumption. We have analysed mathematical and simulation performance of one of the most popular PLC protocol, namely HomePlug Green PHY. PLCs are designed to transfer high level of data rate that is undesirable in-vehicle field because it causes somewhat high protocol overhead. However, according to (T. Gehrsitz, 2014), it is possible to optimize HomePlug GP protocol to meet in-vehicular communication requirements. In this paper, it has been shown that optimized HomePlug GP could be a valid candidate for in-vehicular communication because it provides prioritization according to importance of each message as CAN does. Also, access and transmission delay performance are quite successful according to simulations.

Most performance issues of in-vehicle communication protocols are arisen from access and transmission delay. Other delay types such as processing and propagation delay are insignificant with respect to transmission and access delay. This section aims to show access and transmission delay performance of HomePlug GP, as a power line communication candidate for in-vehicle communication, and compare its performance with CAN (Controller Area Network) and LIN (Local Interconnect Network). Simply, access delay represents the interval between the time when a frame reaches the head-of-line and the beginning of the successful transmission. Fundamentally, if a transmission is not postponed at all and could access to the bus immediately, then its access delay would be zero. On the contrary, if the transmission has to be postponed repeatedly due to constantly occupied bus by other nodes in the network, then access delay could reach significant values. Similarly, transmission delay is defined as the required time to send entire packet.

3.1. Delay Analysis of HomePlug GP

HomePlug GP only provides CSMA as channel access mechanism. Access prioritization of HomePlug GP is adjusted in a two-stage structure. At first, each node with a transmission request sends their priority bits according to its priority level from CAP3 (Highest Priority) to CAP0 (Lowest Priority) as a first stage of prioritization mechanism. After transmission of priority bits, the backoff counter of survival nodes start to count down and the first node that reaches zero will win the access to the bus (Z. Sheng, 2016) (Zyren, 2010) (HomePlug Powerline Alliance, 2013). Since HomePlug GP could impose large protocol overhead which may cause problems for time-critical in-vehicle applications, it is possible to decrease protocol overhead greatly by using only short MPDU (MAC Protocol Data Unit) to transmit data message. It is worth noting that short MPDU is used for ACK (Acknowledgement) and FC (Frame Control) which indicates type of frame (T. Gehrsitz, 2014) (HomePlug Powerline Alliance, 2013), but will be enough to send in-vehicle control message which is usually in the size of 8-bytes.As a novel approach, this paper suggests to use short MPDU format in order to make HomePlug GP as feasible solution for in-vehicle applications in terms of access and transmission delay. The following formulation covers the transmission time of entire packet of suggested HomePlug GP.

$$\mathrm{T_{avg}} = 2 * \mathrm{T_{PRS}} + 3.5 * \mathrm{T_{Slot}} + 2 * \mathrm{T_{Frame}} + \mathrm{RIFS} + \mathrm{CIFS} \qquad (1)$$

$$\mathrm{T_{avg}} = 2 * 35.84 + 3.5 * 35.84 + 2 * \ 110.48 + 26 + 35.84$$

$$\mathrm{T_{avg}} = 479.92\ \mu\mathrm{s}$$

The equation 1 includes $2 * \mathrm{T}_{\mathrm{PRS}}$ that represents priority slot intervals. In a collision-free HomePlug GP contention, backoff counters varies from 1 to 7 so $3.5 * \mathrm{T}_{\mathrm{Slot}}$ is selected as constant to represent average backoff counter interval. In addition, $2 * \mathrm{T}_{\mathrm{Frame}}$ represents transmission time of frame control, the packet that stores payload, and acknowledgement. RIFS (Response Interframe Space), the interval between frame control and acknowledgement, CIFS (Contention Interframe Space), the interval between end of acknowledgment and start of new priority slots, are included as well.

3.2. Delay Analysis of CAN and LIN

CAN has a similar contention mechanism with HomePlug GP. There are 11-bits identifier section in every CAN message, used to prioritize messages. According to (Mayer, 2006), in vehicular domain, powertrain and chassis applications essentially implemented by CAN high speed transceiver supports up to 1 Mbit/s. The body/convenience areas use CAN low speed transceiver that supports data rate up to 125 Kbit/s. In our analysis, we have used 136-bits packet length to simulate CAN. So, the simulations of CAN based on two different data rate, i.e. 1Mbit/s and 125 Kbit/s. The average transmission delays are 136 μs and 1088 μs, respectively (BOSCH, 1991).

LIN has a different contention mechanism than HomePlug GP and CAN. HomePlug GP and CAN are CSMA based protocols, however LIN is a TDMA based protocol. Therefore, there is no real contention mechanism in LIN networks. Access delay of LIN is basically based on the content of LDF (Lin Description File). To conduct a fair comparison, the same amount of packet transmission is assigned to each node with same periodicity in OMNeT++ simulation. The transmission time of an entire packet of LIN with %40 extension is 8680 μs for 20Kbit/s the highest data rate (LIN Consortium, 2010).

4. V2V Communication

4.1. Dedicated Short Range Communications

It has already been mentioned how the primary functionality that Connected Vehicles will contribute towards the Smart City environment is advanced active road safety. A vehicular safety communication network is ad hoc, highly mobile with a large number of contending nodes. The safety messages are very short as it is their useful lifetime-relevance, and must be received with high probability (Q. Xu, 2004). The key enabling technology, specifying the physical and media access control (MAC) layers of the protocol stack used in V2X (ad hoc domain), is DSRC. The DSRC radio technology is essentially IEEE 802.11a adjusted for low overhead operations in the DSRC spectrum (70 MHz in the 5.9 GHz band). It is being standardised as IEEE 802.11p (Association, 2010). The characteristics of wireless technologies targeted for automotive use, presented in Table 1, show that DSRC technology is ideal for Vehicle-to-Vehicle applications.

Stack	Data Rate	Mobility	Bandwidth	Operating Band	IEEE std.
DSRC/WAVE	3-27 Mbps	>60 mph	10 MHz	5.855 - 5.925 GHz	802.11p
Wi-Fi	6-54 Mbps	<5 mph	20 MHz	2.4 GHz, 5.2 GHz	802.11a
Cellular	<2 Mbps	>60 mph	<3 MHz	800 MHz, 1.9 GHz	N/A

Table 1: Comparison among wireless technologies for vehicular use

The IEEE 802.11p amendment defines improvements that enable the use of the IEEE 802.11 in high speed radio environments typical for vehicles. It addresses challenges such as stronger than usual Doppler shifts, rapidly changing multipath conditions (R. Lisový, 2014) and the need to quickly establish a link and carry out V2V exchanges which are, due to the nature of moving vehicles, short (less than 100ms) and transient.

Vehicles equipped with IEEE 802.11p transceivers have the ability to establish links and exchange data with each other Outside of the Context of a BSS (Basic Service Set) – in “OCB” mode, by transmitting a wildcard BSSID (all bits are set to 1). In this mode, the overhead required for the association and authentication procedures at the access control level of each transmitting vehicle (STA) with a BSS Access Point (AP) is eliminated, allowing the establishment of links in fractions of seconds.

4.2. Types of Exchanges

At the physical layer, DSRC defines 7 licenced channels, each of 10 MHz bandwidth: 6 service channels (SCH) and 1 control channel (CCH). All safety messages, whether transmitted by vehicles or RSUs, are to be sent in the control channel, which has to be regularly monitored by all vehicles.

Similarly, there are two supported protocol stacks targeted for use at the two different types of channels, one being the classic Internet Protocol version 6 (IPv6), and a proprietary one known as WAVE Short Message Protocol (WSMP). The reason for having two variations in the upper layers is to distinguish the messages as high-priority/time sensitive and less demanding transmissions such as UDP transactions. A collision avoidance application does not require big datagram lengths or complex packets to be transmitted, rather than very strict probability of reception and little latency. The overhead is 11 bytes, when a typical UDP-IPv6 packet has a minimum overhead of 52 bytes (Li, 2012).

However, WSMP is not able to support the classic Internet applications or exchange of multimedia, taking place in SCH/s and it does not need to since such applications are more tolerant to delay or fluctuations in network performance. By supporting the IPv6 stack, which is open and already widely deployed, third party internet services are easily deployable in a vehicular environment and the cost of deployment would be significantly lower for private investors (compared to using the proprietary WSMP stack for every type of transmission).

Two types of (safety) WSMP messages are sent through the control channel by every DSRC-enabled vehicle;

- **Periodic safety messages**: These are single-hop broadcast status messages (beacons) containing information such as the location, direction, velocity etc. of the transmitting vehicle. These messages are meaningful for little time, so that the receivers can predict the movement of the sender, and after a few seconds become irrelevant. RSUs also utilize these beacons for traffic light status etc. Vehicles are expected to emit these status messages periodically, every 100ms.
- **Event-triggered messages**: Changes in the vehicle dynamics (hard breaking) or RSU status activate the broadcasting of emergency messages with safety information (i.e. road accident warning, unexpected breaking ahead, slippery road).

4.3. Broadcast Safety Communications

It is by now clear that the safety-related applications made possible through CVNs require a low end-to-end delay and high packet delivery ratio. Additionally, since the safety messages will be of broadcast nature, CVNs will be the first large-scale networks where communication is based primarily on broadcast rather than on unicast messages. The choice of an IEEE 802.11 based technology for this kind of network raises some issues (R. Stanica, 2011). The MAC protocol in this family of standards is well known for its inability to cope with large scale broadcast communications, since it was designed for a different use-case and it clearly favours unicast (Rodolfo Oliveira, 2006) communication.

The de facto technique for sharing access to the medium among multiple nodes without central coordination in IEEE 802.11 based networks is the Distributed Coordination Function (DCF). It employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm. Given the large number of contending nodes, especially in an urban environment, it has been found (L. Miao, 2013) that the CSMA/CA algorithm is not reliable enough for broadcast exchanges due to high collision rates.

There are two basic reasons that affect the probability of collisions in such networks; First is the Hidden Terminal problem, a phenomenon which occurs when there are two nodes that are outside the transmission range of each other but will simultaneously transmit to a node that is shared between them. This results in neither packet arriving the destination node. The RTS/CTS mechanism, which is DCF's mechanism of solving this cannot operate in broadcasting systems so that the hidden terminal problem can be tackled.

The second reason is the non-adaptation of the Contention Window (CW) size. The transmission of broadcast packets on a wireless LAN (IEEE 802.11-based protocols) is notoriously unreliable. The MAC layer cannot provide any acknowledgment and retransmission scheme due to the undefined number of recipients and the disparity of the reception conditions between them (Tourrilhes). When the DCF backoff counter expires the data is going to be sent but will not be acknowledged, which means there is no definite way to know if the data actually reached the destination nodes. Collisions would be unrecoverable in this case (Rodolfo Oliveira, 2006), since no intelligent retransmission strategy is implemented for broadcasting. But another drawback of this is that the CW parameter is not doubled on failed transmissions, as in unicast transmissions. Consequently, with smaller CW values the probability of two (or more) nodes choosing the same backoff counter value from the interval [0, CW] is higher, especially in higher network densities, leading to more simultaneous transmissions and eventually collisions.

Single-hop broadcasting is the foundation of communication via DSRC, and since RSUs are currently very sparsely deployed the exchanges of strictly Car-to-Car nature had to be examined. A simulation-based study on the performance of broadcasting via IEEE 802.11p without infrastructure support is presented in the next chapter.

5. Performance Evaluation of CVNs

5.1. Network Simulator

There are a few software environments for simulating a wireless network (J. Lessmann, 2008), of which OMNeT++ 5 is chosen for its many available models, maturity and advanced GUI capabilities. OMNeT++ is a simulation platform written in C++ with a component-based, modular and extensible architecture.

The basic entities in OMNeT++ are simple modules implemented in C++. Compound modules can be built of simple modules as well as compound modules. These modules can be hosts, routers, switches or any other networking devices. Modules communicate with each other via message passing through gates. The connections from one gate to another can have various channel characteristics such as error/data rate or propagation delay.

5.2. In-vehicle

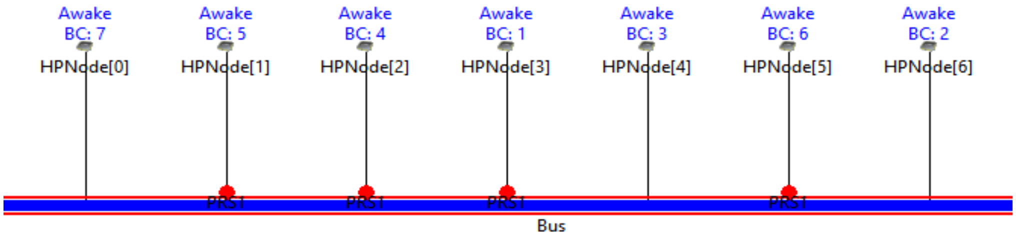

Figure 3: A Simulation Visual Of HomePlug GP

So far, transmission delays of various protocol have been discussed. It has been shown that suggested HomePlug GP outperforms CAN (i.e. when data rate is 125 Kbit/s) and LIN in terms of transmission delay. Fig. 3 illustrates access delay performance of some protocols with various data rate in 7-nodes case. Every sign (i.e. plus, diamond, triangle and circle) in the Fig. 3 shows a transmission and x-axis and y-axis corresponds to initial time of that transmission and how many seconds have been waited in order to initialize the transmission in average, respectively. It should be noted that LIN shows a flat response as it is expected however, rest of the protocols shows fluctuating response. As a result, the simulations based on OMNeT++ showed that proposed HomePlug GP could be a valid and solid candidate for in-vehicle communication and outperforms CAN in some cases and LIN in all cases in terms of access delay performance.

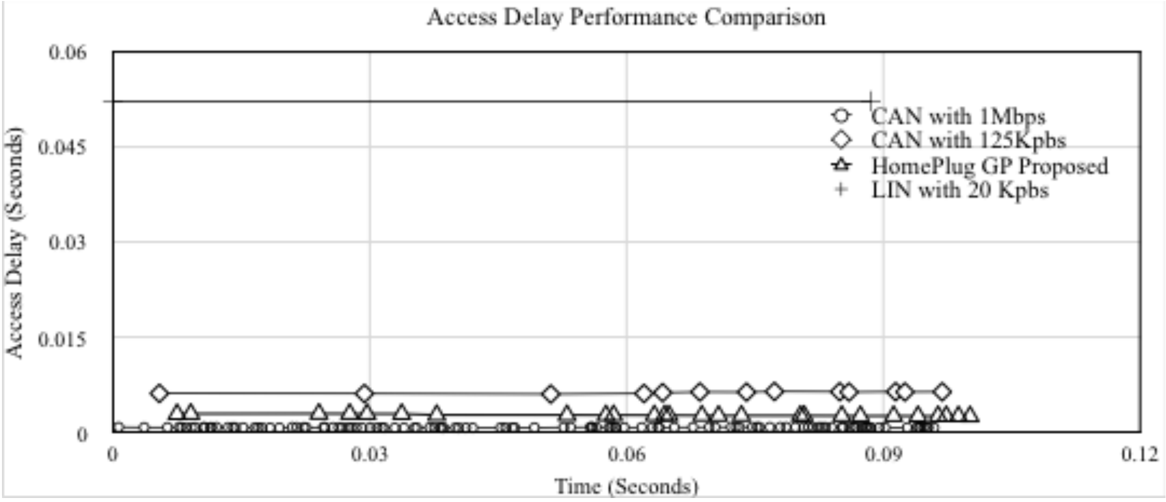

Figure 4: Access Delay Simulation

5.3. Vehicle-to-Vehicle Communications

By using the OMNeT++ simulation environment and some realistic traffic data produced in SUMO, we evaluate IEEE 802.11p for use in the Ad Hoc domain. Every vehicle’s OBU within OMNeT++, consists of a network interface that uses the IEEE 802.11p PHY and MAC and the application layer that describes a basic safety message exchange and a mobility module. Every car broadcasts fixed-size messages periodically, much like the ones specified in the WAVE Short Message Protocol (WSMP).

Since vehicular traffic flow is very complex to model, researchers try to predict road traffic using simulations. A traffic simulation introduces models of transportation systems such as freeway junctions, arterial routes, roundabouts to the system under study. Simulation of Urban Mobility (SUMO) is an open source microscopic and continuous road traffic simulation package which enables us to simulate the car flow in a large road network such as the one in the city of Brighton. Microscopic traffic flow models, in contrast to macroscopic, simulate single vehicle units, taking under consideration properties such as position and velocity of individual vehicles.

Another important reason for choosing OMNeT++ to conduct our simulation experiments is the availability of third party libraries containing many protocol implementations for wireless networks. The INET (INET framework, 2010) framework version 3.2.3 is used for higher layer protocol implementations to achieve Internet connectivity for the OBUs. The VEINS 4.4 (Vehicles in Network Simulation) framework is used for its DSRC/IEEE 802.11p implementation and its ability to bind a network simulation with a live mobility simulation conducted by SUMO v0.25.

The simulation takes place in the southern part of the University of Sussex campus, shown in Fig. 5, an area of 1000x500m where all the parking spaces and most of the facilities exist. This allows us to use realistic network densities, dense during the peak hours and sparse in the evenings. The campus space is large enough so that we can perform experiments on a rather expanded VANET, but small enough so that all the cars can be within transmission range of each other while operating on the maximum DSRC transmission range.

Figure 5: Cars in the University of Sussex Campus simulated in SUMO

By setting the OBU's transmission power high enough to reach the whole campus area the collisions that would be caused by the Hidden Terminals are eliminated, allowing us to track only the packet collisions caused by simultaneous transmissions. For the same reason, the queue length of the MAC layer is set to a number large enough so that there are no lost packets because of queuing.

Each vehicle in our simulation environment emits periodic beacons at a constant rate, seen in Fig. 6. Beacons are not forwarded, since the aim of this study is to study the broadcasting performance for single-hop transmissions. Single-hop broadcasting is the foundational block of V2X safety communications and its performance for large scale scenarios is of concern. Additionally, the infrastructure support for disseminating data to the network is currently sparse, therefore our simulations are not relying on any infrastructure nodes or cellular capabilities as a mandatory building block, focusing on exchanges of strictly V2V nature.

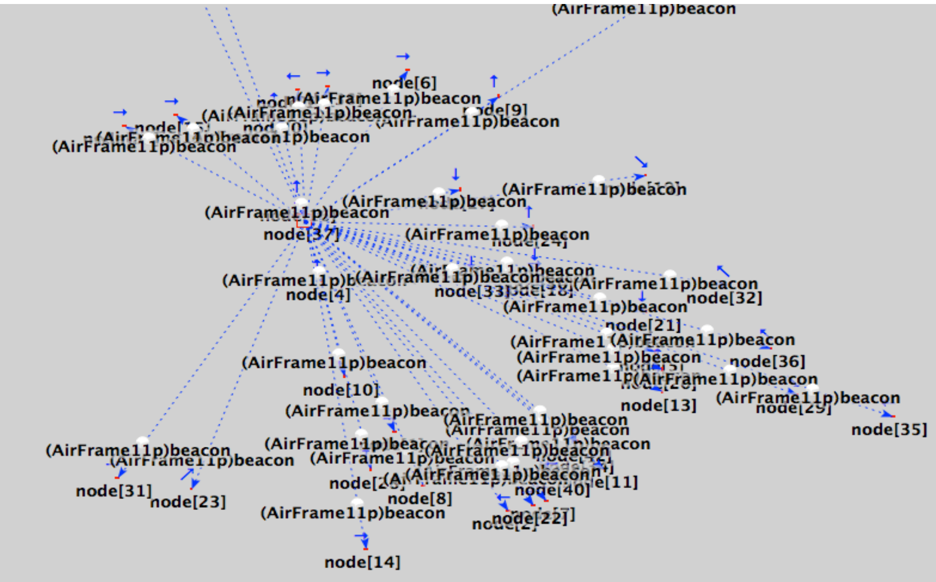

Figure 6: A node emits a beacon to every neighbouring node in OMNeT++

Firstly, the authors evaluate the performance of the network among cars while these periodically broadcast fixed-size messages under variable network densities. The specifications of the transmission such as transmission rate and frequency of sending are according to the DSRC/IEEE 802.11p standard for automotive use, and are fixed at 3 Mbps and 10 Hz respectively. The transmitted messages are safety related, having a size of 200 Bytes. The declining network performance under dense traffic conditions can be observed in Fig. 7. The probability of packet collisions increases with the number of OBU devices that are contending for seizing the medium.

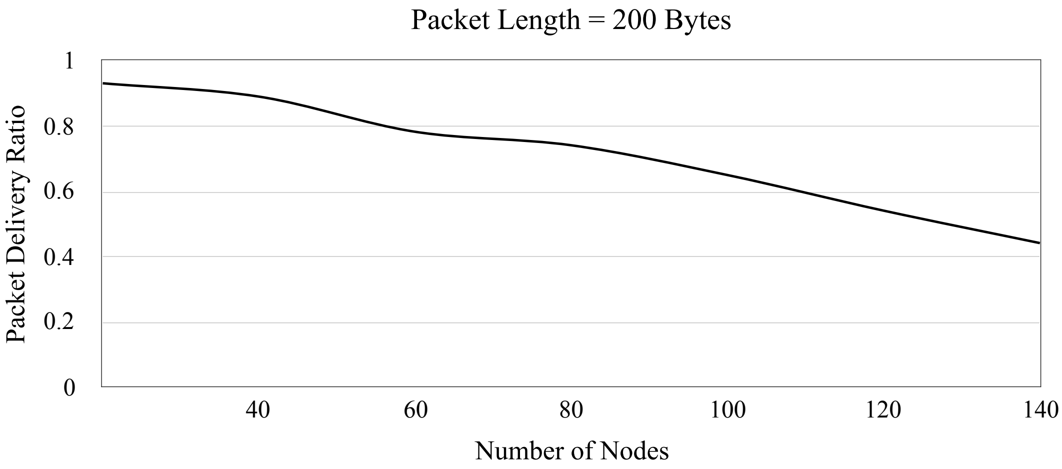

Figure 7: Packet Delivery Ratio for increasing network density for IEEE 802.11p

The second experiment uses the same parameters when it comes to transmission rate and frequency of transmission. This time we examine how the broadcasted packet length affects the network performance, while maintaining a steady network density.

This experiment also targets an inherent problem of the IEEE 802.11 DCF backoff mechanism. Broadcast packets cannot be acknowledged for practical reasons (ACK implosion), so failed transmissions either because of collisions with other packets or channel impairments, cannot be detected. The stations, by not receiving any ACKs for the packets they transmit, cannot adapt their DCF contention window to cope with high traffic load, which leads to poor performance in terms of delivery ratio and delay. In addition to that, the DCF broadcasting mechanism is unreliable since the collided packets are unrecovered, which could lead to nearby vehicles and consequently, drivers, being unaware of safety hazards.

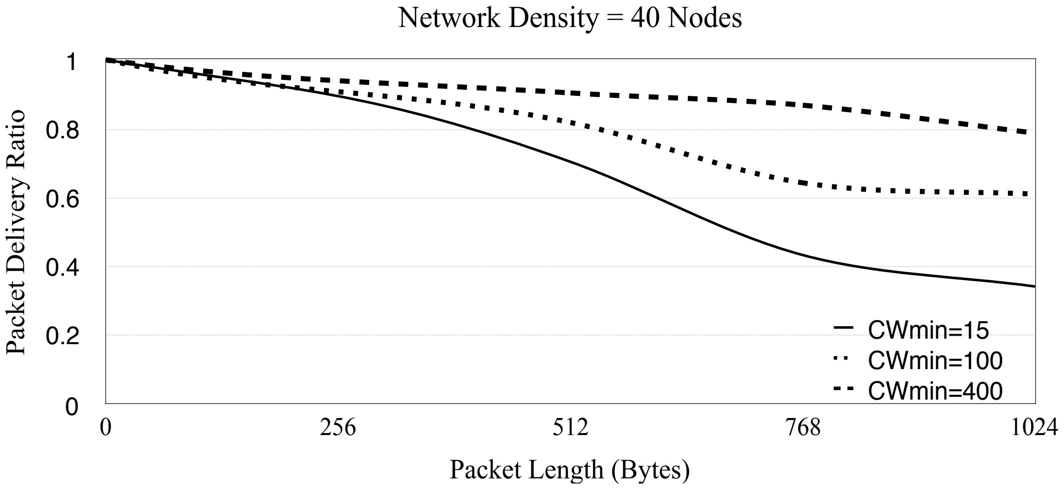

Figure 8: Packet Delivery Ratio versus Beacon Size for IEEE 802.11p

We conduct multiple iterations starting from very small, safety-related packets of 128 bytes, up to packets of 1024 bytes which are generated from the OBUs and would be used for infotainment applications such as map information exchanges, audio and video. The effect of having a larger contention window parameter is very noticeable when broadcasting larger packets, seen in Fig. 8. The performance improvements were apparent to packets larger than 256 bytes. The benefit of contention window adaptation for different types of exchanges is apparent. The trade-off for having bigger contention windows is longer delay, and an adaptive algorithm that tracks the optimal transmission parameters would enhance the performance of such networks.

6. Conclusion

A systemic overview of Connected Vehicles from in-vehicle to perspective has been presented in this paper. The authors review and evaluate an optimised version of HomePlug GP as a potential candidate for in-vehicle networking. The analytical and simulation results validate that the proposed protocol has good potential for such use, in terms of access and transmission delay, data rates as well as simplicity of deployment when compared with traditional solutions such as CAN and LIN.

The researchers continue their study to the ad-hoc domain were the collected data from the proposed in-car networks are broadcasted to single-hop neighbouring vehicles via IEEE 802.11p without any infrastructure support. Exchanges of this nature are the foundation of V2V communication and their performance and reliability in terms of delivery ratio in congested artificial scenarios was evaluated via simulations. It was found that packet congestion in broadcast transmissions has a devastating impact on the performance and reliability of CVN applications, and can potentially be improved by intelligent Contention Window adaptation mechanisms.

7. References

A. Varga, R. H. (2008). An overview of the omnet++ simulation environment. *Proc. of the 1st International Conference on Simulation Tools and Techniques for Communications, Networks and Systems & Workshops* (p. 60:1:60:10). Simutools.

Association, I. S. (2010). *IEEE Standard for Information technology— Telecommunications and information exchange between systems Local and metropolitan area networks— Specific requirements: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications amendment 6: Wireless Access in Vehicular Environments.* IEEE.

BOSCH. (1991). *CAN specification.* R. B. GmbH.

C. Sommer, R. G. (2011). Bidirectionally Coupled Net- work and Road Traffic Simulation for Improved IVC Analysis. *IEEE Transactions on Mobile Computing* , (pp. 3-15).

HomePlug Powerline Alliance. (2013). *Homeplug Green PHY Specification 1.1.1.*

I. Ku, Y. L. (2014). Towards software-defined vanet: Architecture and services. *13th Annual Mediterranean Ad Hoc Networking Workshop (MED-HOC- NET)*, (pp. 103–110).

IEEE. (2010). *IEEE standard for information technology–telecommunications and information exchange between systems–local and metropolitan area networks– specific requirements part 11:wireless lan medium access control (mac) and physical layer (phy) specifications amendment*

6: Wireless access in vehicular environments. Retrieved from https://www.ietf.org/ mail-archive/web/its/current/pdfqf992dHy9x.pdf

INET framework. (2010). Retrieved October 2016, from http://inet.omnetpp.org

J. Lessmann, P. J. (2008). Comparative study of wireless network simulators. *Proc. of Seventh International Conference on Networking (ICN)* (pp. 517–523). IEEE.

K.C.Lee, S.-H. R. (2007). Firstexperience with cartorrent in a real vehicular ad hoc network testbed,. *Proc. of Mobile Networking for Vehicular Environments* (pp. pp. 109–114). IEEE.

L. Miao, K. D. (2013). Performance Evaluation of IEEE 802 . 11p MAC Protocol in VANETs Safety Applications. *Wireless Communications and Networking Conference (WCNC)* (pp. 1663–1668). IEEE.

Li, Y. J. (2012). An Overview of the DSRC / WAVE Technology. *Quality, Reliability, Security and Robustness in Heterogeneous Networks*, (pp. 544–558).

LIN Consortium. (2010). *LIN Specification Package Revision 2.2A.*

M. Behrisch, L. B. (2011). Sumo–simulation of urban mobility. *Proc. of The Third International Conference on Advances in System Simulation (SIMUL 2011).* Barcelona.

Mayer, E. (2006). *Serial Bus Systems in the Automobile Part 2.*

Q. Xu, T. M. (2004). Vehicle-to-vehicle safety messaging in DSRC. *Proceedings of the first ACM workshop on Vehicular ad hoc networks - VANET '04*, (pp. 19-28).

R. Lisový, M. S. (2014). *IEEE 802.11p Linux Kernel Implementation.* Czech Technical University in Prague.

R. Stanica, E. C. (2011). Enhancements of IEEE 802.11p protocol for access control on a VANET control channel. *IEEE International Conference on Communications.*

Rodolfo Oliveira, L. B. (2006). Performance Analysis of the IEEE 802.11 Distributed Coordination Function with unicast and broadcast traffic. *17th Annual IEEE International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC'06)* . Helsinki, Finland.

T. Gehrsitz, H. K. (2014). Analysis of Medium Access Protocols for Power Line Communication Realizing In-Car Networks. *IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, (pp. 1-7). Vancouver.

Tourrilhes, J. *Robust Broadcast : Improving the reliability of broadcast transmissions on CSMA/CA.* Hewlett Packard Laboratories, Bristol.

Z. Sheng, A. K.-A. (2016). A multichannel medium access control protocol for vehicular power line communication systems,. *IEEE Transactions on Vehicular Technology , 65*, 542-554.

Zyren, J. (2010). *Homeplug Green PHY Overview.* White Paper, Qualcomm.