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Hybrid Simulation of Ethernet Based Intra-Vehicle Networks

A dissertation presented
by

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Hybrid Simulation of Ethernet Based Intra-Vehicle Networks

Abstract

As Advanced Driver Assist Systems (ADAS) increase in complexity, it becomes essential to be able to rapidly prototype and test these systems in a reproducible and reliable way. This work explores the problem of simulating intra-vehicle automotive communication networks over which ADAS and other systems communicate through the development and use of new tools and methodologies to assist in the analysis of the performance and impacts of these networks. A comprehensive review of intra-vehicle communication is presented and related literature is explored which details the state of the art, as well as identifying potential solutions to the outstanding requirements of next generation intra-vehicle networks. A novel network simulation testbed based on a Linux platform which has been specifically designed and developed for the purpose of automotive network simulation is central to this work. This testbed platform uses a hybrid real time approach, leveraging lightweight virtualisation technologies to allow for more flexibility and real time extraction of simulation outputs. Thorough testing on double star and daisy chain network topologies demonstrates that the platform's results are in line with those in the literature and shows that, under heavy load generated primarily by six video camera streams, automotive timing constraints may be violated in an Ethernet based in-vehicle network. The real time performance of the testbed is also evaluated and it illustrates that real time streaming up to a bandwidth of 50.7 Mbps can be maintained with a time dilation of less than 7.5 ms. Measurement of the overhead due to the use of virtualisation technologies demonstrates that the performance of the testbed is within 5% of the host system for all measured values.

The methodology and results of a novel image quality experiment facilitated by this platform demonstrates one of many potential real world applications of the developed testbed. An experimental subjective test of 26 subjects is presented which uses a database of real world automotive video containing artefacts resulting from packet loss caused by a simulated network, which was generated as part of this work. The results of the experiment, including Mean Opinion Scores, were recorded from all participants. Image saliency data, which was captured through a custom application developed leveraging an infrared eye tracking device with sub-millimeter precision, demonstrates that packet losses do not significantly effect the visual attention of a viewer. However, the results demonstrate that packet losses in regions of high temporal activity are more salient. A novel image quality metric for use in automotive packet loss effected video is derived which achieves a correlation value of 0.82 with MOS.

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No man is an island, despite doctoral work occasionally making you feel this way, and so I owe a debt of gratitude to the other students that I spent my time surrounded by. The cadre of PhD students in the Department of Electrical and Electronic Engineering were a constant source of advice and friendship through both setbacks and successes. In particular, I'm thankful to the members of the CAR Lab for their support both academically and otherwise, in no particular order, Anthony Winterlich, Damien Dooley, Martin Gallagher, Pat Hurney and Brian McGinley.

Glossary of Terms

ABS Antilock Braking System. 2, 10, 34

ACR-HR Absolute Category Rating-Hidden Reference. 105, 112

ADAS Advanced Driver Assist Systems. 1–3, 10, 26, 38, 44, 45, 49, 51, 60, 65, 68, 83, 84, 87, 88

AUC Area Under the Curve. 111, 112

AUTOSAR AUTomotive Open System ARchitecture. 33–35, 40, 41

AVB Audio Video Bridging. 21–30, 35, 37, 38, 52, 69

CAN Controller Area Network. vii, 3, 10–15, 19, 20, 27, 32, 39, 47, 51, 58, 66, 70

CBS Credit Based Shaping. 23, 24

CDF Cumulative Distribution Function. vii, 76, 78, 79

DCT Discrete Cosine Transform. 94

DMOS Differential Mean Opinion Scores. 106, 110, 111, 113

ECU Electronic Control Unit. vii, 3, 9, 10, 12, 19, 27, 33, 34, 45, 56, 57, 59, 62, 66, 77

EMC Electromagnetic Compatibility. 16, 18, 36

HDR High Dynamic Range. 89

HoLB Head of Line Blocking. 22–25, 30

IEEE Institute of Electrical and Electronics Engineers. iv, v, 11, 14, 17, 21–24, 30, 35, 36, 38, 40, 41, 52, 83, 85

JasPar Japanese Automotive Software Platform and Architecture. 11, 35

LIDAR Portmanteau of light and radar, sometimes Light Imaging, Detection, And Ranging.. 2, 47

LIN Local Interconnect Network. 3, 11–13, 18, 19, 39, 47

LVDS Low Voltage Differential Signalling. 11, 12, 14, 39

LXC Linux Container. ix, 56, 57, 60, 61, 73, 75

MAC Media Access Control. 13

MOS Mean Opinion Score. 88, 90, 107, 110, 113, 117, 119, 121

MOST Media Oriented Systems Transport. 11–14, 19, 27, 39

MSE Mean Squared Error. 94

MTU Maximum Transmission Unit. 22

NSS Natural Scene Statistics. 93, 94

OEM Original Equipment Manufacturer. 11

OPENSIG One Pair EtherNet Special Interest Group. 11, 16, 35, 40, 41

OSI Open Systems Interconnection. 12, 23

PDV Packet Delay Variation. v, vii, ix, 80–82

PLC Power Line Communication. 17, 18, 36

PSNR Peak Signal to Noise Ratio. 88, 90, 91, 94, 117, 119

PVSs Processed Video Sequences. 102

QoE Quality of Experience. 88, 89, 91, 94

QoS Quality of Service. 21, 27, 35, 47

ROC Receiver Operating Characteristic. 111

RTP Real-time Transport Protocol. 67

RTPGE Reduced Twisted Pair Gigabit Ethernet. 17, 35, 36, 41

SM Saliency Map. 109

SSIM Structural SIMilarity index. 88, 90, 91, 94, 117, 119

TDMA Time Division Multiple Access. 12, 13, 26

TSN Time Sensitive Networking. 38, 41

TTCAN Time Triggered Controller Area Network. 13

TTEthernet Time Triggered Ethernet. v, 21, 23, 29–32, 35, 37, 38

TTP Time Triggered Protocol. 13

UESL Upper Empirical Similarity Limit. 112, 114

UTP Unshielded Twisted Pair. 16, 17, 36

VANET Vehicular Ad-Hoc Networking. 12

WFQ Weighted Fair Queueing. 21

Statement of Originality

I hereby declare that the work contained in this thesis has not been submitted by me in the pursuance of any other degree.

Name:

Date:

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Chapter 1

Introduction

1.1 Motivation

Advanced Driver Assist Systems (ADAS) are increasingly becoming an important component of in-vehicle systems. As processing power grows and consumer electronic systems shrink in size, the possibilities for in-vehicle safety and entertainment systems grow. Developments that were the subject of research papers just a few years ago are becoming standard features on even low-end vehicles. These include systems such as lane departure detection [1], adaptive cruise control [2] and automatic parking systems [3].

The motivation for systems such as these is often safety. Though in general the number of road fatalities is trending downwards, as reported in a 2004 World Health Organisation report, road traffic injuries were the largest cause of death in Europe for people between the ages of 5 and 30 [4]. Studies have found that up to 75% of road crashes are as a result of driver error [5]. These statistics and others like them have been a primary motivation for the development of much more sophisticated ADAS such as lane departure detection, adaptive cruise control and driver monitoring systems. With the increase of the prevalence of driver assist applications, the required associated communications infrastructure must improve to accommodate the extra bandwidth and timing requirements of complex ADAS systems.

ADAS offer a path towards fully autonomous vehicles which is appealing for a number of reasons including increased safety, better fuel economy, and enhanced mobility for people who are unable to drive. Early indicators from trials of autonomous vehicles are positive. Schoettle et al [6] found that, while there have been accidents involving autonomous vehicles, the autonomous vehicle was not at fault for any of these accidents and any injuries that did occur were of a lower severity than from conventional vehicles.

Bengler et al [7] divide the evolution towards fully autonomous driving into three stages. Firstly, proprioceptive sensing, the deployment of sensors within the vehicle which lead to intelligent algorithms such as Antilock Braking System (ABS). Secondly, exteroceptive sensing, referring to the recent proliferation of sensors which allow the car to react to the outside world such as cameras, LIDAR and others. The final stage in the evolution of electronics within vehicles is referred to by the authors as "Sensor Network", which is the cooperation of each of the sensors already mentioned combined with intelligent ADAS leading to fully automated driving.

The development of this ”Sensor Network” approach within the vehicle necessitates the associated development of faster, more complex automotive intra-vehicle communication networks. Automotive specific technologies such as CAN, Local Interconnect Network (LIN) and Media Oriented Systems Transport (MOST) have been utilised up to now to provide communication links between the various ECUs within the vehicle. However, it has become clear that these technologies can not keep pace with the advances of ADAS in terms of scalability, bandwidth and cost. For this reason, several other networking technologies have been proposed to match the increasing requirements of the automotive industry.

The design and implementation of automotive networks is a costly and time consuming exercise and, as such, multiple techniques have been proposed which allow for the verification and testing of designs using software network simulations. These simulations are more flexible than creating hardware networks and can allow automotive network designers to test multiple network configurations quickly and thoroughly, without hardware expense. Rather than reimplementing common network stacks, components and protocols, it is common for networking researchers to use a network simulation library to construct such simulations.

It is important at all stages of the automotive network and electronic development process to be aware of the implications of design decisions on networking behaviour. The use of a software based network simulation platform can assist in decision making; however, its usefulness is limited somewhat if it does not use traffic from real applications. It is also highly useful if these simulations can be carried out in real time so that the effects of potential networking issues can be seen at the application layer as they would be seen by the end user, in this case the driver of the vehicle. This constitutes the majority of the main motivation for this thesis, that is, to develop a platform that can be used at all stages of the development process of automotive algorithms and systems to accurately and reliably model the network implications of design decisions on all facets of automotive applications.

1.2 Contributions

This thesis is concerned with the development of novel simulation techniques for Ethernet based automotive networks and the utilisation of these techniques to investigate network effects on automotive image and video quality. The following are the major contributions of this work, listed here to help guide the reader.

- A comprehensive review of current state of the art intra-vehicle networking technologies, including physical layer standards, link layer protocols, and middleware technologies.
- The development of an Automotive Ethernet network simulation platform for the evaluation of Ethernet network topologies and configurations.
- Integration of real world applications into the simulation platform, allowing

direct integration and analysis of driver assist applications with the simulated network.

- Evaluation of the strengths and weaknesses of the hybrid automotive simulation technique, with a focus on time dilation and synchronisation for automotive applications.

- An automotive specific video quality database of 10 real automotive video samples, each processed at 5 different levels of packet loss. The database is complete with human saliency (eye tracking) data, and subjective Mean Opinion Scores to determine the influence of packet loss on subjective Quality of Experience for automotive video.

- The application of the developed simulation platform in a 26 user image quality study examining the effects on user attention of network packet loss for automotive environments.

1.3 Thesis Structure

The remainder of this thesis is structured as follows. Chapter 2 presents an up to date and comprehensive review of the state of the art in the field of automotive intra-vehicle networks. It analyses all levels of the network stack, from the physical medium up to middleware platforms in use for next generation automotive applications. Chapter 3 details the creation, evaluation and testing of a novel hybrid approach to the simulation of automotive networks using lightweight virtualised containers. It describes in detail the architecture of the platform, as well as investigating the underlying interactions between the network simulation and the host hardware. In Chapter 4 the testing of two network topologies is presented, as well as comprehensive testing to detail performance and capabilities of the simulator as well as its limitations. Chapter 5 demonstrates the potential of a hybrid approach to network simulation by detailing its application in a subjective test carried out with 26 subjects to evaluate the effects of network packet loss on the quality of experience of human subjects. A novel database of 10 real automotive samples is presented. This database is augmented with eye tracking data as well as Mean Opinion Scores. Finally Chapter 6 revisits some important and novel findings of this thesis, while presenting opportunities for future work in the area.

1.4 Publications

Several publications have resulted from this work, they include one workshop publication, a conference publication, as well as three journal publications.

1.4.1 Workshop Papers

- *An ns-3 Based Simulation Testbed for In-Vehicle Communication Networks.* Tuohy, S., Glavin, M., Jones, E., Hughes, C., & Kilmartin, L. In 27th Annual

UK Performance Engineering Workshop, July 2011.

1.4.2 Conference Papers

- *Next Generation Wired Intra-Vehicle Networks, A Review.* Tuohy, S., Glavin, M., Hughes, C., Jones, E., Trivedi, M., & Kilmartin, L. In IEEE Intelligent Vehicles Symposium, June 2013.

1.4.3 Journal Papers

- *Intra-Vehicle Networks: A Review.* Tuohy, S., Glavin, M., Hughes, C., Jones, E., Trivedi, M., & Kilmartin, L. In IEEE Transactions on Intelligent Transportation Systems, Vol. 16, No. 2, Pages 534-545, April 2015. **Chapter 2**

- *Evaluating the Influence of Packet Loss on Visual Quality of Perception for High Bandwidth Automotive Networks.* Tuohy, S., Winterlich, A., Mc Ginley, B., Glavin, M., Jones, E., Denny, P., Kilmartin, L. Elsevier Signal Processing : Image Communication, Vol. 43, Pages 15-27, April 2016. **Chapter 5**

- *Hybrid Testbed for Simulating In-Vehicle Automotive Networks.* Tuohy, S., Glavin, M., Jones, E., Hughes, C., & Kilmartin, L. In Elsevier Simulation Modelling Practice and Theory, Vol. 66, Pages 193-211, August 2016. **Chapters 3 & 4**

Chapter 2

State of the Art

2.1 Introduction

There are a large number of competing networking technologies in the automotive domain at all levels of the network stack. This chapter serves as a comprehensive review of the most popular and relevant automotive networking technologies as explored in the literature.

Historically, each new electronic sensor or application in a vehicle has been implemented by adding a new stand-alone ECU device and subsystem. This has led to in-vehicle networks growing in both size and complexity in an organic fashion. This often leads to many complex, sandboxed, heterogeneous systems in a single vehicle. This is undesirable as there can be a number of different network protocols in use, which inhibits communication between systems. It also increases cost to the manufacturer in terms of hardware costs, development costs and support costs.

To overcome these problems, communication links were established between relevant ECUs, allowing ECUs to share data with one another and enabling more advanced functionality. For example, the ABS subsystem may communicate with a seat belt pre-tensioning system to activate it in the event of a collision. This approach is very inefficient as, with point to point links, the number of connections required increases exponentially with the number of ECUs installed in the vehicle. To address this issue, multiple ECUs are connected to one another using bus-based networks such as Controller Area Network (CAN) [8] or FlexRay [9]. Current generation automotive network technologies such as these are described in more detail in Section 2.2. The use of bus based networks is an improvement on the point to point link system; however it presents its own problems since, as the number of ECUs connected to a bus increases over time, the bandwidth consumed increases significantly. The question of bandwidth does not generally manifest as a significant issue in control applications within the vehicle due to the limited bandwidth requirements of the sensors involved. However the bandwidth issue has been brought into sharp focus through the introduction of infotainment and camera based ADAS. These applications require significantly more bandwidth than traditional control applications and, as such, the technologies and techniques used on current networks are insufficient for the needs of a next generation in-vehicle network architecture.

Recently, there has been a general desire within the automotive industry to streamline the development of these systems through standardization of technologies between manufacturers, leading to greater reuse and interoperability between Original Equipment Manufacturer (OEM)s and manufacturers. Most major automotive companies are members of one or more special interest groups and bodies centred around this goal. These bodies include the One Pair EtherNet Special Interest Group (OPENSIG) [10], the AVnu alliance [11] and the Japanese Automotive Software Platform and Architecture (JasPar) [12].

This chapter includes discussion on physical middle and application layer technologies in use in vehicles. It also includes discussion and attempts to identify trends in the field for the future.

2.2 Physical Layer

2.2.1 Automotive Specific Technologies

For a number of years, technologies such as CAN [8], FlexRay [9], LIN [13], Media Oriented Systems Transport (MOST) [14], Low Voltage Differential Signalling (LVDS) [15] and IEEE 1394 Firewire [16] have been used in vehicles. Each of these communication bus technologies, with the exception of LVDS and Firewire, have been developed specifically for the automotive environment. Table 2.1 provides general information on the maximum bitrate, medium and transmission protocol of each of these technologies.

Navet et al. [17][18][19] previously carried out reviews of automotive specific communication protocols. These papers are excellent sources for technical information on automotive communication technologies, which is outside the scope of this chapter. In this section the most important characteristics of the most common protocols are discussed. Nolte et al. [20] gave an overview of many more of the less commonly used protocols. An in-depth exploration of the technical specifics of CAN, LIN and FlexRay can also be found in [21]. Finally, Karagiannis et al. [22] and Gerla et al. [23] provide excellent and comprehensive overviews of the general area of vehicular networking, focused mostly on inter-vehicle networking and Vehicular Ad-Hoc Networking (VANET).

CAN is an automotive specific bus standard developed by Robert Bosch GmbH released in 1986 [8]. It defines layer 1 and layer 2 functionality of the Open Systems Interconnection (OSI) network model. CAN is typically used to transmit control traffic between ECUs within the vehicle. It generally uses a nine pin D-SUB connector and allows for a maximum bus speed of 1 Mbps at lengths of up to 40 metres. Messages are encapsulated in frames with a maximum data field size of 64 bits. It does not use a Time Division Multiple Access (TDMA) based Media Access Control (MAC) layer like the Time Triggered Protocol (TTP)[24] but nonetheless is currently very popular in the automotive domain as a communication bus for event triggered communication. More deterministic behaviour can be obtained through the use of the Time Triggered Controller Area Network (TTCAN) [25] standard at the session

Table 2.1: Current automotive physical layer technologies

Protocol	**Bitrate**	**Medium**	**Protocol**
LIN	19.2 Kbps	Single Wire	Serial
CAN	1 Mbps	Twisted Pair	CSMA/CR
FlexRay	20 Mbps	Twisted Pair/Optical Fibre	TDMA
MOST	150 Mbps	Optical Fibre	TDMA
LVDS	655 Mbps	Twisted Pair	Serial/Parallel

layer.

MOST was developed to primarily support networking of multimedia data. The maximum possible bandwidth as defined by the MOST150 standard is 150 Mbps which makes it much more suitable than CAN for multimedia data transmission.

FlexRay is an automotive networking standard that was developed by the FlexRay consortium which disbanded in 2009. Members of the FlexRay consortium before its dissolution included BMW, Volkswagen, Daimler and General Motors. The main advantages of FlexRay over CAN are its flexibility, higher maximum data rate (10Mbps) and its deterministic, time triggered, TDMA behaviour. However, FlexRay nodes are more expensive than CAN nodes which can be unappealing for high volume manufacture. It provides constant latency and jitter through clock synchronization, these characteristics mean that is is often used as part of 'drive-by-wire' applications where deterministic performance is critical. TTP is a similar standard and was compared with Flexray by Kopetz et al. in [26].

LIN [27] is an inexpensive, broadcast, master-slave, serial communication bus developed in the late 1990s by the LIN Consortium consisting of a number of automotive manufacturers. It arose from a desire for a cheaper alternative to CAN for less important elements of the in-vehicle network.

2.2.2 Non Automotive Specific Standards

LVDS [15] is a high speed signalling standard that uses twisted pair copper cables. While not explicitly developed for automotive applications, the high bandwidth made possible by LVDS (up to 655 Mbps) has made LVDS an attractive option for automotive camera manufacturers.

IEEE 1394 [16], more commonly known as Firewire, is a general computer communication bus standard often used in consumer video cameras, which has been proposed as a candidate backbone network for automotive infotainment traffic [28]. It is often supported by automotive grade cameras from various manufacturers, however it has been superseded by Ethernet based devices in recent years.

2.3 Automotive Ethernet

Ethernet [29] is a commonly utilized communication bus which is the communication technology of choice for much of the Internet due to its cost, speed and flexibility.

A motivating factor for Ethernet for use in vehicles is the increased bandwidth that it offers. Legacy technologies such as CAN and MOST were developed specifically for automotive applications and, as such, offer an advantage in that they are tailored with in-vehicle communication in mind. At the time of their inception, the bandwidth levels provided were sufficient for the applications that they supported i.e. by modern standards, low bandwidth control applications, but this is no longer the case.

Ethernet has already superseded CAN bus connections for interfacing with diagnostic equipment due to its increased bandwidth. In [30] the authors give the example of the time taken to flash the firmware of a vehicle. Using a CAN based network this process takes 10 hours when flashing an 81 MB firmware update. Using an Ethernet network and a much larger 1 GB update, this procedure takes 20 minutes.

Driver assistance applications are a rapidly expanding area of research. The placement of a variety of sensors around and throughout a vehicle allows for the development of new and exciting safety features such as collision avoidance, lane departure detection, traffic sign classification, blind spot detection, driver intent detection [31], pedestrian detection, automatic cruise control and many others. Such sensors are being used to communicate information to the driver in useful and innovative ways [32].

These applications take advantage of high bandwidth sensors around the vehicle, such as 24GHz short range or 77GHz long range radar sensors [33], ultrasonics, infra red cameras [34] and optical video cameras [2].

2.3.1 Unshielded Twisted Pair Ethernet

Many of the advantages of Ethernet (not directly related to the higher bandwidth that it provides) are due to the proposed use of Unshielded Twisted Pair (UTP) cabling. The OPENSIG describes itself as a group aiming to "address industry requirements for improving in-vehicle safety, comfort, and infotainment, while significantly reducing network complexity and cabling costs" [10]. It promotes the use of UTP cabling by automotive manufacturers and counts among its members BMW, Daimler, Nissan and Renault.

Cabling in an automotive environment is a complex problem. Much of the physical space within a vehicle is taken up by the passenger cabin and cables cannot be routed through this area. Unshielded twisted single pair Ethernet consists of a single twisted copper wire pair, making it small, flexible, lightweight and cheap to manufacture. It allows manufacturers to make space and weight savings in the routing of cable harnesses whilst also improving available bandwidth.

The use of UTP cabling allows Ethernet to fulfil important automotive specific requirements such as electromagnetic compatibility or Electromagnetic Compatibility (EMC) requirements. BMW testing [35] has shown that 100 Mbps full-duplex, unshielded single twisted pair cabling meets automotive EMC requirements. Moreover, Hank et al [36] have explored in detail a commercially available, automotive-targeted 100 Mbps product, from network equipment vendor Broadcom.

However, 100 Mbps Ethernet is only capable of carrying compressed video streams

[37]. The IEEE Reduced Twisted Pair Gigabit Ethernet (RTPGE) Study Group [38] was founded in November 2012 specifically to standardize modifications of the IEEE 802.3 standard to allow for the use of 1 Gbps Ethernet on fewer than three pairs of twisted copper cable. This is required as the current 802.3 standard does not support 1 Gbps operation on fewer than four twisted pairs. The aims of the group specifically mention the use of Ethernet as a communication network in vehicles as a primary driver behind the development of these new additions to the 802.3 standard. The name of the new standard is called IEEE P802.3bp and it is expected it will be used for a large variety of applications, especially in the automotive and avionics domains [39].

2.3.2 IEEE 1901

IEEE 1901 is a standard for high speed communication via electric power lines. Power Line Communication (PLC) is most commonly used to extend Ethernet capabilities using the already existent power infrastructure in a building.

It is already in use in some electric vehicle charging systems and it is seen as a potential alternative to UTP based Ethernet for next generation communication architectures. It combines communication and power cables, meaning large savings in space required to route cables through the vehicle.

Strobl et al. [40] provide an introduction to the implementation of PLC in an automotive setting, implementing an automotive network using SIG60 PLC transceivers.

This implementation seeks to replace low bandwidth networks such as LIN and operates at 115.2kbps. The system implements a master-slave type network and is quite basic in operation, allowing a single frame on the bus per cycle to ensure collision avoidance. However, for certain applications where cabling space may be at an absolute premium, a PLC network could potentially extend an Ethernet network via powerlines.

Nouvel et al. have published a number of papers in the domain of PLC communication for automotive applications: [41][42][43][44][45]. Of these papers, [44] provides a detailed analysis of the potential PLC standards that have been investigated for use in automotive scenarios as well as EMC results and comparisons. Nouvel et al. concluded, similar to Strobl et al., that powerline communication in automotive environments, while not suitable as an end to end solution, may be useful in scenarios where cabling space and costs are severely restricted. In [43] a commercial PLC based solution was created and tested, concluding that it provides throughput which exceeds that of the FlexRay protocol.

2.3.3 Topologies

Though it is clear that Ethernet has the potential to provide a large number of benefits to in-vehicle networks, the question of how to network the devices within the vehicle together remains.

Automotive devices are generally split into different functional domains, this involves grouping applications and sensors together into sub domains by functionality or by physical location. As mentioned in Section 1.1, existing networks have developed organically and display significant heterogeneity. CAN may be used for body control data, FlexRay for safety critical applications, LIN for small serial control messages and MOST for infotainment data. This variety of different networks leads to difficult to maintain, inflexible combinations of protocols and topologies. An illustration of this configuration can be seen in Figure 2.1. On the left side of Figure 2.1 is a representation of this type of complex, multi-technology network.

To rectify this undesirable situation, a top down, designed approach is required. Lim et al. [46] propose that each of the separate domains within the vehicle report to a master ECU, which then facilitates inter-domain communication, abstracting the detail of each individual network from the Ethernet network backbone. This approach is also proposed by Hank et al. [36] and an example of such a network is illustrated on the right side of Figure 2.1.

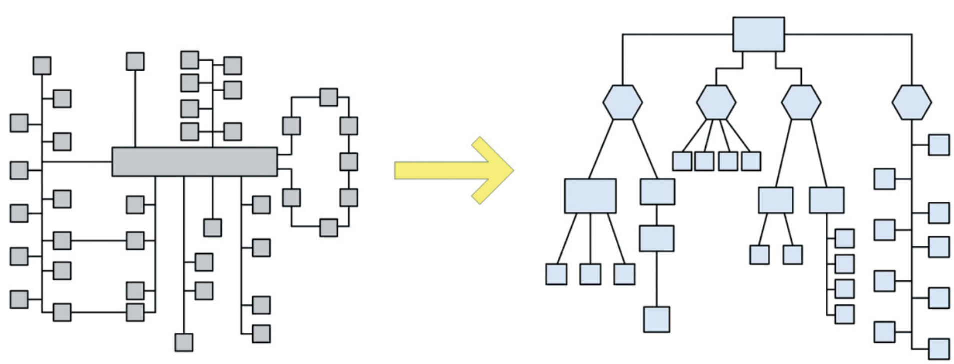


Figure 2.1: Migration from heterogeneous architecture to future top down approach

2.4 Link Layer Protocol

As has been discussed in Section 2.2, the bandwidth capabilities, cost and flexibility of 802.3 Ethernet make it a very attractive option for the interconnection of automotive devices. However, Ethernet, in its default configuration, does not provide deterministic or real time functionality which is required of the automotive domain. Contemporary Ethernet networks generally utilize TCP/IP to ensure delivery of packets, however this would not be suitable for a safety critical automotive environment as it does not provide maximum delay guarantees.

Network communication can very generally be split into two types: event-triggered and time-triggered. Traffic latencies within an event triggered network can be probabilistically modelled based on network parameters while those in a time triggered systems are fixed. Ethernet and CAN are both event triggered network protocols while FlexRay is time triggered. Both time triggered and event triggered traffic exists on current automotive networks which is a motivating factor behind the use of multiple networking technologies in a single vehicle. In order for Ethernet to provide a unified automotive network backbone, it must be modified to support deterministic delivery of safety critical traffic.

This means that without modification, for certain safety critical applications such as 'drive-by-wire', Ethernet cannot be used as it cannot guarantee deterministic behaviour.

There are a number of proposed approaches to overcome this problem in the automotive domain, three are most commonly found in the literature: IEEE 802.1Q, Audio Video Bridging (AVB) Ethernet, and TTEthernet.

2.4.1 IEEE 802.1Q VLAN Tagging

802.1Q is a simple technique that is used to priority tag packets in an Ethernet network. Though intended for use in tagging packets in VLANs, it has been used in a number of literature publications in automotive systems [47][48][49][50]. 802.1Q operates by adding an extra field to the Ethernet header of a packet which allows for a priority value to be stored in a 3 bit field, thus supporting 8 (2^3) priority levels. When used with a traffic queuing algorithm such as Weighted Fair Queueing (WFQ) it can function as a lightweight Quality of Service (QoS) algorithm.

Rahmani et al. [48] use 802.1Q tagging to compare the performance of ring and double star network topologies, concluding that the double star configuration is more resource efficient and flexible than a unidirectional ring topology. Lim et al. [47] provide a performance comparison of IEEE 802.1Q and IEEE AVB which is explored in more detail in Section 2.4.2. Although the use of 802.1Q (in the automotive environment) is declining in the literature in favour of the more complex AVB, it has been shown to provide a lightweight, widely supported and reliable method to improve the QoS of automotive networks.

Lee et al. [51] propose an 802.1Q based system which has been shown to meet even hard real time delay constraints, with no modification to the network stack or protocols. This method relies on limiting the Maximum Transmission Unit (MTU) of messages that have the same destination port as hard real time messages, thus limiting the effects of Head of Line Blocking (HoLB). They show through both simulation and mathematical analysis that this can be used to provide real time guarantees to traffic in an 802.1Q based network. On set up, a bootstrapping approach is taken, whereby each application requests resources and the network calculates and sets the maximum MTU so that the required delays are met.

2.4.2 Audio Video Bridging

Introduction

Audio Video Bridging consists of a set of four IEEE standards designed to provide time synchronized streaming of audio and video sources using 802.3 Ethernet.

The standards that together comprise AVB are as follows :

- IEEE 802.1AS: Timing and Synchronization for Time-Sensitive Applications (gPTP),
- IEEE 802.1Qat: Stream Reservation Protocol (SRP),
- IEEE 802.1Qav: Forwarding and Queuing for Time-Sensitive Streams (FQTSS), and
- IEEE 802.1BA: Audio Video Bridging Systems

Each of these standards plays a role in the provision of time synchronized performance on an Ethernet network. 802.1AS utilizes the IEEE 1588 Precision Time Protocol standard to allow for precise time synchronization between nodes. This involves the use of a *grandmaster* node which communicates timing information to all other nodes on the network.

802.1Qav handles priority allocation of streams by adding data to the Ethernet header in a very similar way to the 802.1Q standard detailed in Section 2.4.1. In this sense AVB can be seen to encapsulate the functionality of IEEE 802.1Q while adding more features, at the expense of less universal hardware support and a more complex system. The specification uses a form of Credit Based Shaping (CBS) which delays the sending of packets so as to reduce bursts. This increases the latency in the network as packets spend some time at switch ports waiting to be transmitted but it greatly decreases jitter on the network due to the output conforming to pre-specified parameters. However, HoLB can still cause further delay and jitter due to the lack of pre-emption in the current AVB standard.

Streams within an Ethernet AVB capable network can reserve bandwidth, using the 802.1Qat standard, by issuing an SRP message. Resources are then allocated at both stream end nodes and each of the transmit nodes along the path at the Link Layer (or Level 2) of the OSI model. An important and useful feature of AVB, which is absent from TTEthernet, is online stream reservation. TTEthernet requires stream reservation to be carried out offline. Finally 802.1BA provides functionality to identify AVB profiles and nodes within a network.

AVB supports two traffic classes with different latency guarantees. *Class A* traffic maps to 802.1Q priority level 3 and offers a delay guarantee of 2ms. *Class B* provides delay guarantees of 50ms and is mapped to 802.1Q priority level 2 [52].

Although the initial scope of the AVB standard was for the time synchronized delivery of audio and video content for stage and live environments, its potential for use in other scenarios that require time sensitive delivery of traffic was quickly realised. The interest in its use in these domains has led the IEEE group in charge of the AVB standard to begin work on a second revision set to include several enhancements to facilitate automotive, industrial and consumer requirements. While working on these improvements, the group realised that the protocol can be useful for more types of traffic than audio and video streams and therefore renamed the standard Time Sensitive Networking or TSN. A number of tier-1 automotive manufacturers and component manufacturers [11] support these operations and the development of associated IEEE standards. The proposed improvements include pre-emption, which would mitigate the problem of HoLB, a topic explored in more detail in Section 2.4.2.

Aeronautical and Industrial Applications

Imtiaz et al. [53] carried out a performance study of the suitability of AVB technology for industrial applications, comparing AVB with 802.3 Ethernet and also AVB using a CBS. The authors noted that the transmission of a large best-effort traffic frame (i.e a HoLB scenario) can interfere with the operation of normal AVB transmission. They concluded that, for the particular simulation scenario tested, AVB does not offer advantages over 802.3 Ethernet.

In [54], the same authors propose a method to overcome the effects of HoLB in Ethernet AVB networks. In order to ensure that a real time priority packet is not blocked on the network by a large, non-real time packet, the authors propose stopping transmission of the non real time packet and fragmenting it, transmitting the real time packet and finally, resuming transmission of the non real time packet again. Simulated results from this work showed promise that the use of this strategy would mitigate the effects of HoLB on AVB networks and, as such, should be considered for the second generation of the AVB standard.

Heidinger et al. [55] created a prototype AVB capable network for an aeronautical audio based network. The authors concluded that the network was a viable replacement for legacy networks and provided satisfactory delay values but raised concerns about certification of AVB capable hardware.

Automotive Research

Lim et al. have carried out a number of analyses of Ethernet AVB specifically with regards to its use in the automotive domain [47][56][57]. In [47] the authors provide a comparison of the performance of 802.1Q priority scheduling and the more advanced AVB in a simulation environment using the OMNeT++ network simulator.

The end to end delay results of this comparison show 802.1Q prioritisation outperforming AVB for the transmission of control data within the vehicle when that control data is assigned the highest 802.1Q priority value and is assigned a best-effort priority value within the AVB network.

However, when extra load is introduced to the network, AVB *Class A* or *Class B* video traffic does outperform the same traffic in the 802.1Q network. The authors conclude that more work is required in the area to ensure that, within an AVB network, control traffic manages to satisfy its real time requirements.

Further to this, Moon et al [58] found that for control traffic, 802.1Q has lower latency when compared to AVB; however AVB has lower latency when used for ADAS type loads. The authors conclude that, due to this, 802.1Q is more suitable to control systems traffic whereas AVB is better suited for ADAS traffic.

Alderisi et al. [59] found that AVB functioned very well for a double star automotive network containing camera, infotainment and ADAS application traffic. For workloads up to $\sim$ 90Mbps, jitter and latency values were found to meet the automotive requirements as described in [60].

It is possible to extend AVB to accommodate a TDMA method of operation, as demonstrated by Meyer et al [61], this could be used to improve the reliability of messages within an AVB environment; however experimental results have shown increased latency in this type of system.

Work to ensure the suitability of AVB in a harsh automotive environment has been carried out by Kern et al. [62]. The authors performed tests on a simple prototype network to ensure that AVB capable devices perform as expected under varying automotive temperature conditions. The authors conclude that temperatures between -10°C and +70° C do not cause problems for AVB capable consumer devices.

The slow synchronisation times for AVB networks has been adressed by Diarra et al [63], who propose a number of methods to decrease the time taken for devices to perform timing synchronisation within an automotive network by up to 25 times. The fastest method only requires 2.5% of the time of the original standard, with a small trade off in the form of increased likelihood of errors.

In [52], Zinner et al. address the issue of integrating legacy automotive networks with Ethernet AVB networks, specifically MOST and FlexRay networks. This is a pertinent problem as it is unlikely in the near term that all devices in the vehicle will be immediately replaced with Ethernet capable replacements. Instead the change is likely to be gradual and evolutionary rather than revolutionary. Because of this, Ethernet will likely have to coexist with some legacy networks for a period of time.

Specifically, in [52] the authors propose a system to translate the QoS guarantees provided by MOST and FlexRay to an AVB network, while crucially also maintaining synchronization between clocks across the bridged networks. This work however relies on simulation and somewhat ideal networks and more work is required to validate its feasibility in a real network with multiple FlexRay ECU devices and clusters.

Herber et al. [64] demonstrate a method of bridging CAN and Ethernet AVB networks utilising a number of improvements over other methods, including frame encapsulation and also provide analysis of the effect of different scheduling algorithms on this type of network configuration.

Theoretical Analysis

Much of the work cited above involves the use of simulation or prototype networks to test the performance and characteristics of AVB networks. However, more formal mathematical explorations of the technology are also important. Work of this nature can also be found in the literature.

Diemer et al. [65] provide a mathematical worst case timing analysis of the AVB standard for an industrial application, resulting in a formulation for the worst case end to end latency value in an AVB network, as a function of switch transfer time, packet blocking by other packets and traffic shaping delay.

In [66], Queck provides an analysis of the AVB standard through the application of network calculus [67]. In this work, the authors provide a formal derivation of the worst case end to end delay values under the assumptions of the Network Calculus framework and apply these to a case study consisting of a double star automotive network with 3 traffic classes. The authors conclude that, under the assumptions made in deriving the worst case analysis, AVB, and specifically the use of 802.1Qav as a queuing paradigm, meet the timing requirements of automotive traffic.

2.4.3 TTEthernet

TTEthernet or Time Triggered Ethernet [68], first presented by Kopetz et al. [69][70][71], is another Ethernet based candidate for real time communication in automotive or industrial networks. It is designed to allow for the coexistence of time triggered real time, synchronized communication with lower priority event triggered messages over Ethernet. This is implemented by applying a Time Division Multiplexing scheme with a time granularity of 60μs, on top of existing 802.3 Ethernet.

TTEthernet supports three different traffic types, Time Triggered (TT), Rate Constrained (RC) and Best Effort (BE). TT traffic takes priority over all other types while RC traffic is guaranteed to be supplied with a predetermined bandwidth level. BE traffic follows standard Ethernet procedures.

TTEthernet is standardized in SAE AS6802 [72] by the Society of Automotive Engineers and developed by TTTech. Similar to Ethernet AVB, in order to use the system, switches within the network must implement the TTEthernet standard.

Steinbach et al. [73] compared the suitability of TTEthernet with FlexRay using calculations on typical scenarios for both standards. Jitter and latency were found to be comparable between both technologies and taking into account the much higher bandwidth available in TTEthernet, it was found to be a viable replacement for FlexRay networks for time triggered communication in vehicles.

Simulation based results, also from Steinbach et al. [74] validate closely the mathematically demonstrated results from [73].

Table 2.2: Automotive Network Traffic Timing Requirements

Traffic Class	**Max End-to-End Delay**	**Service Rate**
Control Data	2.5ms[76]	10 - 100ms
Safety Data (Video)	45ms[50]	0.05 - 1ms
Infotainment Data	150ms [77]	~1ms

The papers explored in this section only seek to give an overview of research found in the literature as it relates TTEthernet to automotive applications. TTEthernet is also being investigated in a number of other domains where real-time communication is required such as aeronautical and industrial applications [75].

2.5 Implementations

Due to the competitive nature of the automotive industry, it is perhaps unsurprising that details on prototype implementations of the technologies described in Section 2.4 are difficult to find. However, there are a number of sources in the literature which detail prototype systems.

Steffen [76] and Rahmani [78] detail a prototype system built in a BMW 530d vehicle which utilizes the 802.1Q priority scheduling algorithm. This prototype includes two Ethernet switches and a Head Unit connected in a daisy chain topology. Devices connected to the switches include engine control modules connected via a CAN - IP gateway, an IP enabled camera module, a 3G mobile data network connection, wifi access point and an Audio/Video server operating using Universal Plug and

Play (UPnP). The prototype system was found to work well, including the bridging of CAN traffic onto an IP network, though exact test details and metrics were not detailed.

In [79], Bartols et al. analysed the performance of TTEthernet using commercially available hardware, a basic network topology and TTTech developed TTEthernet protocol stack. The results of this real world testing showed latency values when using a TTEthernet switch were much more stable than those obtained when using an 802.3 Ethernet solution.

Muller et al. [80] provide details on an implementation of a TTEthernet based platform for automotive applications. The system is not as complex as that detailed in [76] and consists of 3 prototype TTEthernet nodes, created using an ARM based System on a Chip and a traffic generator. The platform was tested under a variety of different traffic load scenarios and was found to operate reliably with all TTEthernet deadlines met for both Rate Constrained (RC) and Time Triggered (TT) traffic. While this system is more basic than any real automotive implementation i.e. it has significantly fewer nodes, it does show that TTEthernet represents a viable technology for deterministic in-vehicle networks.

Table 2.3 provides a summary breakdown of the papers discussed in this section and is intended to allow the reader to easily reference and locate all papers corresponding to a particular subject found in the literature.

Table 2.3: Intra-Vehicle Link Layer Networking Paper Comparison.
S = Star, R = Ring, DS = Double Star, DC = Daisy Chain, T = Tree, MS = Multistar, P2P = Point to Point

	Priority Algorithm			**Method**			
Author	**802.1Q**	**AVB**	**TTE**	**Simulation**	**Prototype**	**Analytical**	**Topology**
[56]				✓			DS
[81]	✓			✓			S, DC, T
[47]	✓	✓		✓			DC
[57]		✓		✓			DC
[51]	✓			✓			DS
[50][48]	✓			✓			DS, R
[82]			✓	✓			S
[83]		✓	✓	✓			T
[59]		✓		✓			DS
[84]		✓	✓	✓			S, DS
[85]				✓			S
[79]			✓		✓		P2P
[76]	✓				✓		DC
[80]			✓		✓		P2P
[65]		✓				✓	MS
[66]		✓				✓	DS

2.6 Middleware

The use of Ethernet in vehicles allows for more interoperable and compatible networks. Tier 1 manufacturers can easily switch component suppliers provided that all manufacturers use Ethernet as a common communication bus.

However, for the most part, the advanced applications that are made possible by high bandwidth automotive networks operate on proprietary software stacks. This means that they can require extensive porting or rewriting for new architectures, chipsets and hardware revisions.

AUTomotive Open System ARchitecture (AUTOSAR) [86] is an industry led proposed solution to these issues. It consists of a partnership of automotive companies and component manufacturers including BMW, Daimler, Toyota, GM, Ford, Volkswagen, Volvo, Renault, Hyundai, Honda, Mitsubishi and many others.

AUTOSAR seeks to provide a common, scalable middleware interface between applications and automotive ECUs. This allows for much easier interoperability between vehicle models and even between manufacturers. AUTOSAR provides a method whereby the specific hardware implementation is abstracted from the application developer, allowing for more rapid and generalised development [87]. Some of the basic concepts underlying the AUTOSAR specification are explained in more detail in [88].

The use of AUTOSAR allows for the abstraction of ECU functionality into a middleware layer. The use of a common middleware framework means that applications can be developed once and deployed multiple times, thus saving development time and alleviating complexity.

In addition, the standard seeks to make the creation of automotive applications quicker and more efficient, by allowing developers to use standardized, higher level development tools.

Kum et al. [89] discuss approaches whereby existing automotive applications and functionality can be migrated to the AUTOSAR platform. Hermans et al. [90] provide a case study for the integration of AUTOSAR into the development of an automotive ABS application. The authors found that the use of AUTOSAR did not negatively affect the development process and did not necessitate changes to legacy testing methodologies.

There is much research in the literature concerning the integration of AUTOSAR development into existent testing and embedded development work flows [91][92][93][94]. There are also a number of papers examining the underlying timing and scheduling performance of the platform, such as [95][96].

It is clear from the depth of testing and analysis of the platform in the literature, as well as the near universal membership of the AUTOSAR partnership by automotive manufacturers and suppliers, that it very likely represents the future of the development of automotive applications.

2.7 Discussion and Concluding Remarks

The preceding sections provide an overview of the current state of in-vehicle automotive networking. This area can often be overlooked by networking researchers, with areas such as Vehicle to Infrastructure (V2I) and Vehicle to Vehicle (V2V) communications often seen as more interesting. However, these networks all must interface with the in-vehicle network and thus it provides the backbone for all next generation automotive applications.

It is becoming more and more clear that Ethernet will provide the backbone for the next generation of in-vehicle networks. All major automotive manufacturers belong to one or more special interest/working groups which promote the use of Ethernet in the next generation of vehicles (OPENSIG, AVnu, JasPar etc.). The development and standardization of QoS mechanisms such as TTEthernet and IEEE AVB provide reliable tools for the development high speed, safe and deterministic in-vehicle Ethernet networks. The ongoing development of AVB version 2 and the formation of the IEEE RTPGE study group point to steadily increasing demand for automotive grade Ethernet solutions.

Many questions have already been answered as to the suitability of Ethernet in vehicles, as demonstrated throughout this chapter. Primarily these centre around a number of discrete areas.

Selection of PHY Medium

The Ethernet PHY is not suitable for direct deployment in a commercial vehicle, mostly due to space and potential EMC issues. This has led to the development of UTP solutions such as Broadcoms Broad-R-Reach system [36] which meet the more stringent automotive EMC requirements [35].

This has also led to the formation of the IEEE RTPGE, which will allow Gigabit operation using a physical interface of less than three twisted pairs copper cables.

This group has been developing a standard which is known as IEEE 802.3bp.

Although there are potential alternatives such as Firewire, PLC and wireless communication, Ethernet has assumed a dominant position over these technologies. Since Ethernet is a widely used and recognized IEEE standard, the automotive industry will benefit from its continued evolution and improvement.

However, the development of the IEEE RTPGE working group is in the early stages and it will be a number of years before commercial vendors will produce hardware which is suitable for Gigabit Ethernet deployment in vehicles. It also may not address in sufficient detail fault tolerance concerns of automotive manufacturers. For this reason, it seems likely that manufacturers will continue to deploy control networks based on the FlexRay protocol, potentially in tandem with Ethernet deployments [97].

Suitability of Link Layer Protocols

It is in the area of Link Layer protocols that much of the research of in-vehicle networks in the literature has taken place. There are a number of competing approaches and it is currently somewhat unclear as to which direction the automotive industry will progress. AVB and TTEthernet have both been shown to be viable protocols for use in an in-vehicle network. 802.1Q has been demonstrated to be a workable solution but does not meet automotive requirements under certain conditions.

Though the choice to use Ethernet based technologies for the next generation of in-vehicle networks appears to have been made by many manufacturers, uncertainty arises as to the nature of the protocols used to guarantee deterministic performance. AVB and TTEthernet meet these requirements; however, they are competing standards and are not mutually compatible. They require manufacturers to commit to one or the other as, in order to use either standard, all nodes on the network must be AVB/TTEthernet aware.

A competitive simulation based analysis of AVB and TTEthernet carried out by Steinbach et al. [83] showed that both technologies provide comparable results in the delivery of time sensitive automotive traffic (similarly, Alderisi et al. [84] carried out a comparison of AVB and TTEthernet, with the same conclusions as found in [83]). Though AVB is shown to be affected more than TTEthernet by cross traffic on the network, it offers advantages in the reliable streaming of multimedia data.

Given that there is little difference between the two standards in terms of performance, other metrics must be used to judge the superiority of one technology over the other. For a number of reasons it can be proposed that AVB offers the better solution for the timely delivery of automotive traffic for next generation wired Ethernet networks for a number of reasons demonstrated in this section; the volume of supporting work for AVB in the literature, the membership of several tier 1 automotive manufacturers in the AVnu alliance, IEEE support and the development of AVB version 2 Time Sensitive Networking (TSN) which caters more to automotive requirements, and lastly, the advantages for streaming media provided by AVB as shown in [83]. The vast majority of the bandwidth used by a next generation automotive network will be consumed by multimedia, either infotainment or active computer vision based safety systems and it is thus advantageous to use AVB. Its perceived weaknesses in the transmission of control traffic should be improved upon by the work of the IEEE TSN working group and this could ensure that it becomes the industry accepted standard for in-vehicle automotive networking.

There is the potential, as mentioned in [84], for the coexistence of AVB and TTEthernet in a single vehicle. In this scenario, each technology would handle different classes of traffic on the network, with AVB focusing on infotainment and video based ADAS while TTEthernet handles lower level safety critical applications. This is an interesting possibility and it would take advantage of the strengths of each technology; however it may cause fragmentation and complexity similar to that currently seen in CAN, FlexRay, MOST, LVDS and LIN based networks. However, since the underlying physical communication medium is the same (i.e. Ethernet), the introduction of hybrid switches or components which support both standards may potentially make this a viable and cost effective possibility. Zeng et al [97] excellently summarise the qualitative differences between the two technologies, demonstrating that each has strengths and weaknesses in the areas of maximum latency, jitter characteristics and fault tolerance. It is difficult to quantitatively pick a *winning candidate* between the two technologies and, as such, it remains to be seen which will become the de facto choice for automotive manufacturers.

There are, as yet, open questions in relation to these technologies. As shown by Table 2.3, much of the research available in the literature details simulation verification. There are comparatively few papers which detail real world implementations of the technologies. This may be influenced by the fact that the creation of a real world test environment involves considerable investment in hardware and is often facilitated through support from automotive manufacturers who may be unwilling to release technical implementation details due to the competitive nature of the automotive industry.

Software Platform

The first technical team exploring the possibilities of a common automotive industry standard architecture formed in 2002. AUTOSAR has been steadily developing for a number of years. Although ostensibly progress is slow, it has been continuous, measured and thoroughly documented. Automotive manufacturers each have proprietary specialised platforms that have developed organically over the course of many years, thus migration to a standard architecture is a gradual process. AUTOSAR reports that a number of manufacturers have already migrated to fully compliant AUTOSAR Basic Software and most core partners (Daimler, BMW, Peugeot Citroen, Toyota etc.) have targeted 2016 for the completion of their migration to the platform. The stated goal of the AUTOSAR alliance is to enable innovation by providing a common architecture and, in the coming years, this will allow for greater innovation, interoperability and cooperation between manufacturers.

2.7.1 Conclusions

It is clear from the body of work in the literature and significant industry interest through groups such as AVnu and OPENSIG that Ethernet represents the most likely and promising candidate for the standardization of next-generation automotive networks. The benefits of a wide-scale adoption of Ethernet are wide ranging and include bandwidth improvements, cost savings, and improved implementation flexibility. Since Ethernet is a widely used and recognized IEEE standard, the automotive industry will benefit from its continued evolution and improvement.

It is likely that the shift toward fully Ethernet based automotive networks will be a slow and considered process. It is not currently feasible to replace all in-vehicle devices with Ethernet-enabled replacements. Therefore, it is likely that Ethernet will function as a high-speed backbone network, at first, coexisting with legacy technologies until such time as it becomes cost effective to migrate to a full end-to-end Ethernet solution.

Automotive manufacturers are extremely sensitive to component costs. This can lead to high volume and therefore lower cost technologies having an advantage over others. This may lead to manufacturers preferring Ethernet based communication where component costs are already low due to its common use in other domains.

The body of research analyzed in this chapter points toward a single conclusion:

As automotive networks become more complex, standardization of approaches becomes more and more appealing to manufacturers. This is happening at all levels of the automotive communication stack and is gaining momentum, with organizations such as IEEE RTPGE, IEEE TSN Working Group, OPENSIG, the AVnu alliance, and AUTOSAR coordinating an industry-led push toward extensible and cost-effective standards that will drive the development of in-vehicle networks.

This chapter presents a compelling argument that, as in-vehicle technology becomes more and more complex, there is a drive to standardize approaches across the industry, allowing manufacturers to focus on innovating with exciting applications built on similar foundations. This provides an excellent framework for the future expansion and improvement of in-vehicle systems, leading ultimately to greater driver comfort and, most importantly, safety.

Chapter 3

Hybrid Network Simulation Testbed

3.1 Introduction

Modelling the behaviour of automotive networks is an important and valuable tool in the design and implementation of intra-vehicle networks. It is not always feasible or cost effective to construct a physical prototype of systems at each stage in the development of a design and therefore, simulation tools can be useful to explore different configurations. Recently a range of approaches have been developed to model the behaviour of these types of networks, notably by Lim et al. [81][47], Hintermaier et al. [98] and Alderisi [84]. The focus of this chapter is on introducing and analysing a novel modelling technique and platform for the evaluation of automotive networks.

As automotive networks increase in complexity, so does the network traffic that they carry. Increasingly this includes automotive video streams from cameras placed around the vehicle. These cameras are vital for the development of ADAS that lead to safer vehicles. Therefore it is important that these streams are taken into consideration when designing and evaluating intra-vehicle networks. It is proposed that the integration of real time automotive video network streams into a testbed (for the purposes of this work, the term *testbed* is used to mean a hybrid network simulation platform which integrates both virtualised and simulated nodes) allows for more realistic and useful simulations. This is done by simulating using a hybrid approach which involves the integration of traditional traffic generators and real video network streams onto a novel simulation platform.

The motivation for the development of this platform is as a powerful tool to assist in the testing and development of automotive video systems and novel ADAS algorithms. To illustrate the utility of the platform more clearly to the reader, the following motivating examples are given of scenarios for which the developed platform is and has been useful.

- Video ADAS applications can be tested in real time on a hybrid simulation network early in their development. These results can be used to gain a better understanding of how the algorithm will perform in a real vehicle at an early stage.

- Failure scenarios can be easily and clearly demonstrated and tested at each point in an algorithms development, allowing researchers and developers to investigate the effects of packet loss or high jitter values on image quality for ADAS applications, or the effects of link loss on ECU load.

- Subjective tests on automotive video ADAS applications can be carried out, for example, measuring the subjective effects on image quality of network related artefacts.

While this platform does not seek to completely replace real world testing of these algorithms, it has proven to be a useful and powerful tool in the development of a variety of automotive video systems and ADAS algorithms [99] as well as providing a deep insight into the human considerations that must be taken into account when developing automotive systems.

The remainder of this chapter is structured as follows, a brief overview of the requirements of various traffic types typically found on an automotive network is detailed. The use of Ethernet as a replacement technology for the protocols and standards currently used in the automotive space is discussed in depth and previous work related to this topic in the literature is explored. A novel automotive network testbed platform is then proposed and its design and implementation are detailed. Experiments carried out to validate the performance and capabilities of the implemented architecture are also presented. Finally conclusions drawn from the development and evaluation of the simulation platform are outlined.

3.2 Automotive Network Traffic

Often, several of the communication technologies explored in Chapter 2 will be used in a single vehicle. As already noted there is significant diversity in the capabilities of these technologies and this in itself is a significant motivator of interest in the use of a common communication standard in the next generation of in-vehicle networks.

These communication technologies are often used in conjunction with one another, each carrying a particular class of network traffic within a vehicle. These classes of traffic can be broken down into a number of sub domains based mainly on their real time requirements as described by Rahmani et al [48].

3.2.1 Traffic Categories and Requirements

Though there are often many different traffic sources in a modern automotive network, these are generally separated into a number of discrete categories based on their characteristics and requirements. In this section a brief overview of the characteristics of these different types of traffic is given. Table 3.1 gives the specific timing requirements of these categories as found in the literature [76] [50] [77]. These requirements must be met if an Ethernet based network is to be used to replace current generation networks.

- Low Bandwidth Real Time Control Applications

Table 3.1: Traffic Timing Requirements

Traffic Class	**Max End-to-End Delay**
Control Data	2.5 ms[76]
Safety Data (Video)	45 ms[50]
Infotainment Data	150 ms [77]

These are subsystems within the engine of a vehicle which have low bandwidth requirements but high QoS requirements, e.g. suspension and braking systems. Generally in modern vehicles these systems utilise a low speed CAN network which provides low bandwidth but high reliability.

- Other Control Applications

  There are other control subsystems within a vehicle with lower QoS demands. These include systems which control aspects of the vehicle which are not safety critical. Examples of these types of systems would be air conditioning control or electrically controlled windows. In general, the low cost, low bandwidth LIN network will be used for these types of systems.

- Safety Data

  Modern vehicles come equipped with an increasing number of built-in driver assist safety subsystems. These can include adaptive cruise control using LIDAR or radar sensors, lane departure detection using front and rear optical cameras [1], and night time pedestrian detection using infra-red sensors [34].

- Infotainment Data

  Infotainment traffic encompasses all network traffic related to entertainment and driver information systems within a vehicle. This includes GPS systems, display only camera feeds, audio and visual entertainment and miscellaneous other network traffic (e.g. a 3G/UTMS Internet connection).

3.3 Ethernet as an Automotive Communication Technology

Ethernet [100] has been a dominant networking standard in mainstream computing for almost 30 years. Its combination of high speed, low cost and flexibility provides a powerful backbone for many different network types.

An in-vehicle Ethernet based network is capable of carrying multiple, mega-pixel resolution, real time video streams. Current generation in-vehicle camera systems are often VGA (640x480 pixels) resolution at 30 frames per second. Future systems will likely integrate mega-pixel and multi mega-pixel sensors to improve image quality. The superior image quality of mega-pixel resolution video cameras allows driver assist applications to be more accurate and provide more functionality; however they can require substantial bandwidth as shown in (3.1) (which assumes that there is no compression at the camera level and 8 bits per each of the red green and blue channels).

$$\begin{aligned} Bandwidth &= (Width) * (Height) * (Frames\ Per\ Second) * (Bits\ Per\ Pixel) \\ &= (1280)(960)(30)(24) \\ &= 884.74 \text{ Mbps} \\ &= 110.59 \text{ MBytes/s} \end{aligned} \tag{3.1}$$

As of mid-2016, a number of camera modules which output raw video of this type are already available. Cameras which output raw video decrease the time taken from image capture to transmission by removing the encoding/decoding steps, at the expense of much higher bandwidth requirements.

In current generation vehicles, the use of at least one camera is becoming standard, while high end vehicles may contain multiple cameras for a variety of applications. It is expected that the number of optical cameras placed in vehicles will increase in order to provide a number of driver assist applications [101]. A next generation in-vehicle multi-camera system may contain six or more cameras working in tandem. Figure 3.1 shows a real world application of a multi-camera system, in this case a parking assistance application.

In-vehicle networks often carry safety critical information and, as driver assist computer vision applications become more important as part of ADAS, it is likely video streams from these cameras will be safety critical also. An in-vehicle network must be able to guarantee the timely arrival of such traffic. The provision of such guarantees will be essential for Ethernet to provide the communication infrastructure

Figure 3.1: This is a top-down view generated by a suite of on-vehicle cameras, with the camera outputs processed and stitched together to yield a seamless 360 degree view around the vehicle (shown here performing a parking manoeuvre).

for next generation vehicles.

In the development of this hybrid testbed, it is assumed, as in other similar systems in the literature [81] [76], that Ethernet will be used to carry all automotive traffic, with the exception of a separate CAN based legacy system which is modelled as operating over Ethernet through a CAN - Ethernet bridge. It is likely that CAN systems will remain in vehicles for some time, as pointed out in [102], however data on the CAN bus may also be useful in some Ethernet ADAS applications and so, in these simulations, it is also included it on the Ethernet network. The primary focus of this platform is to examine automotive video traffic for a number of purposes. However, in order to remain as faithful as possible to real automotive networks, all traffic types are included in the simulation whilst the results in this chapter focus on those which are relevant to video traffic.

3.4 Related Work

There have been a number of efforts to simulate automotive networks in recent years, through a number of methods, none of which are similar to the approach employed in this chapter. However it is useful to discuss a number of these approaches in order to place this work in the correct context.

Daoud et al. [103] used the OPNET network simulator to test a single star Ethernet network with two classes of network traffic, control traffic and multimedia infotainment traffic, concluding that end to end delay constraints were met for a 1000 Mbps network and two traffic types.

Rahmani et al. [50] investigated ring and double star topologies for potential use in an automotive network using the OMNET++ platform [104] and concluded that in order to guarantee end to end delay times for heavily loaded networks, using 100 Mbps Ethernet links, traffic shaping of flows is necessary so that delay and jitter values achieved remain stable during bursts of variable bit rate traffic.

Lim et al. [81] examined single star, daisy chain and tree topologies from an automotive perspective with 100 Mbps Ethernet links using a number of traffic generators (also using the OMNET++ platform). The authors concluded that, while the star network provided best performance, it can be subject to large delays in a potential worst case scenario due to the reliance on a single processing node. Lim et al. [47] also provide a performance comparison of IEEE 802.1Q and IEEE AVB.

Hintermaier et al. [98] implement a prototype 100 Mbit full duplex automotive network making use of Linux computers to emulate IP cameras outputting H.264 [105] encoded video synchronised using IEEE 1588.

From a control systems standpoint, systems similar to that proposed in this work have been proposed by Quaglia et al [106]. The authors create a comprehensive and formally correct co-simulation framework combining two elements, a network simulator (in this case SystemC) and Matlab for design and modelling of control systems, with a specific focus on time synchronisation between the two platforms.

The CANOE family of products developed by Vector [107] is a commercially available suite which supports the simulation and development of automotive networks. These devices are rarely used in the literature due to their prohibitive cost; however there are some papers which investigate automotive networks using these devices, namely Nguyen et al [108] and Li et al [109]. Both papers focus primarily on automotive control systems, however the CANoe.Ethernet module may allow for simulation of complex Ethernet networks such as that modelled in this work.

3.5 Hybrid Testbed

In the literature, most automotive simulations are carried out using the discrete event simulation model, that is; the simulator maintains a clock and as soon as it is finished processing an event, it moves on to the next event. If there are no events to be processed in a particular time period, the simulator simply jumps to the next event. In order to implement a hybrid simulation, the simulator must account for the real world clock as it is interfacing with real hosts and packets must be processed within the simulation in real time. This introduces a number of timing considerations that are explored in more detail in Section 3.6.

3.5.1 Linux Container Based Testbed

It is important when creating simulations that they mirror real world performance as closely as possible and for this reason the presented platform employs a hybrid approach. This differs from traditional network simulation in that the system integrates real world traffic across a simulated network. This approach allows simulations to utilise accurate and realistic network traffic flows and removes reliance on in-built traffic generators of the particular simulation platform in use. Linux containers were used to achieve this functionality.

Many well known virtualisation systems such as Xen[110], VMWare [111] and KVM [112] use a hypervisor approach to virtualisation, that is, a guest operating system runs on top of a hypervisor application which handles translation of system calls to the underlying host operating system. Container based visualisation instead uses the kernel of the host operating system directly and separates processes from the host operating system through namespaces [113].

Due to the nature of this type of virtualisation and the requirement for the virtualised containers to use the same kernel as the host operating system, this limits the supported execution environments to Linux hosts and Linux based guests.

This limitation is a disadvantage of this approach over the use of a hypervisor based virtualisation solution, however, it offers performance and other advantages [114].

This virtualisation technique allows for less flexibility in the guest operating system that may be used, but makes containers much more lightweight than hypervisor based solutions. The difference between these two approaches is illustrated in Figure 3.2.

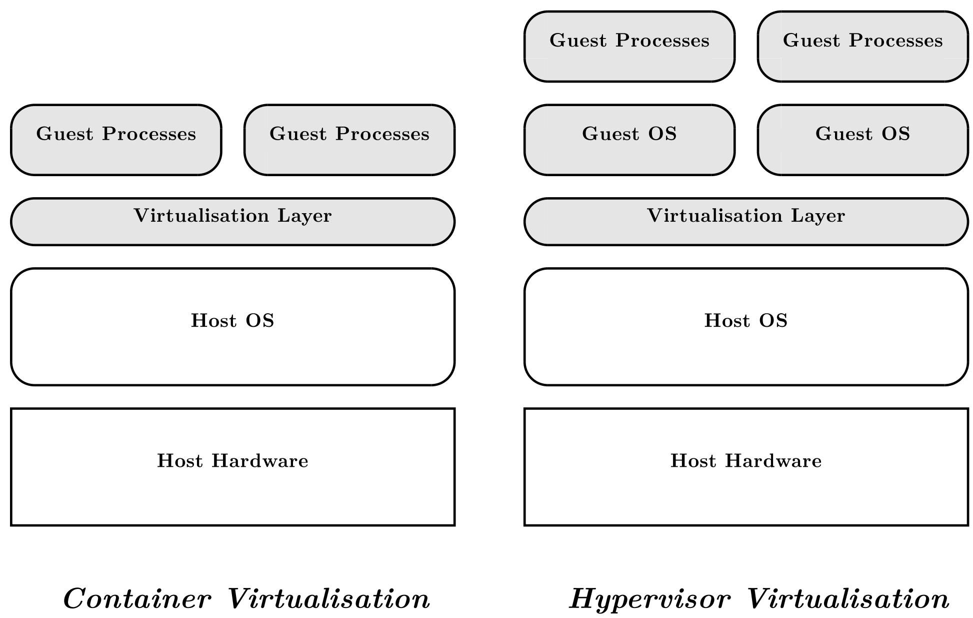


Figure 3.2: Illustration of container based virtualisation compared to hypervisor based virtualisation.

For the purposes of this research, the ns-3 network simulator [115] was chosen. ns-3 allows integration between a simulation network and Linux containers through the use of tunnel and tap devices (TUN/TAP). An illustration of this functionality can be seen in Figure 3.3.

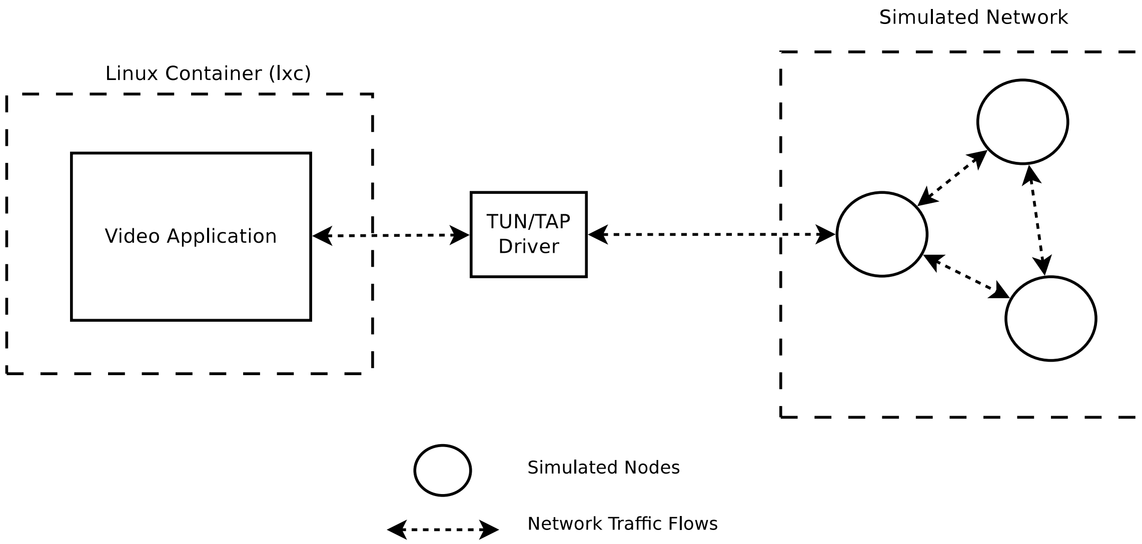


Figure 3.3: Illustration of traffic flows between simulated network and video application running in Linux container.

There are other network simulators which offer similar functionality such as OmNeT++ [116], however ns-3 was selected for this work for a number of reasons, primarily concerned with performance. Weingartner et al [117], as well as Lacage [118], have clearly shown that there are performance benefits to the use of ns-3. [118] in particular focuses on the performance and suitability of ns-3 for interfacing with real devices.

Using the Tap Bridge functionality of the ns-3 simulation platform, a simulated network device, in this case a Linux based host, appears as though it is a real network device or Network Interface Card (NIC). All packets sent to this network device from the real host are routed through its native network stack and into the ns-3 simulation.

The same process happens in reverse when packets are sent to the simulated network device associated with the Linux virtual machine from the simulation. In this way two real hosts can communicate with each other via a simulated network.

For the purposes of this work, this means that Linux containers can take the place of streaming cameras, ECU receivers and any in-vehicle device. In order to validate that the modelling methodology is realistic and to investigate how accurately LXC devices emulate real hosts, an analysis was completed on the performance of the containers compared with real hosts. There are a number of comparisons of this type in the literature, such as Xavier et al. [114] and Beserra et al. [119]. These authors have found that LXC containers consistently outperform all other virtualization techniques across a number of metrics with differences between LXC network latencies and native latencies consistently in the order of microseconds. Lamps et al [120] demonstrated that LXC containers are extremely time accurate when compared to real hosts, again in the order of microseconds.

3.5.2 Node Types

As mentioned in Section 3.2.1, there are a number of different classes of network traffic commonly found on in-vehicle networks. These traffic types translate into a number of different traffic generating ECUs that are required to be included in an automotive network simulator. The following devices were created in software and are available for use in the hybrid testbed.

- Optical Cameras

  - The bandwidth consumed by the video sources is altered to simulate different camera hardware. More information on the bandwidth used by these devices is contained in Section 4.2.1. All cameras transmit using UDP. In a real time automotive camera system, the use of TCP is not useful since frames need to be processed in real time.

- CAN Gateway

  - The data rate of a CAN bus is limited by its length. Since a vehicle is a small physical space and CAN connections within are generally $< 10m$, a bit rate of 400 kbps is assumed. A frame size of 20 bytes is used, this represents the maximum frame size allowable by the CAN bus standard.

- Radar Source

  - A 77Ghz radar source operating at a data rate of 10 Mbps is modelled, with a service rate of 1 ms.

- Infotainment Sources

  - A typical in-vehicle infotainment system is modelled with two H.264 encoded 1080p video streams at a data rate of 5 Mbps each.

- Miscellaneous Traffic

  - This represents miscellaneous other traffic present on the in-vehicle network, such as Internet traffic from a wireless or broadband network or user generated infotainment traffic. It has a data rate of 15 Mbps provided by two Constant Bit Rate (CBR) applications at 10 Mbps and 5 Mbps both over TCP. The TCP protocol was chosen for this traffic as it is likely that external traffic introduced from wireless networks would be carried over TCP.

- Receiver Nodes
  - These nodes receive the traffic sent from all other nodes. Within a real vehicle this would correspond to a powerful ECU where image processing and other functions would be carried out on the received streams. Due to its safety critical nature and tight delay requirements a separate receiver node is dedicated to receiving and processing control traffic.

3.6 Validation and Results

The performance of the network stack significantly impacts simulation of network devices. Due to the architecture of container based virtualisation, i.e. that the containers use the same kernel as the host, the overhead of the virtualisation should be very low or negligible. In order to validate this the following tests were performed.

3.6.1 Kernel Level Benchmarking

An analysis was carried out using the *ku-latency* tool [121] to isolate any kernel overhead in processing packets. This tool allows measurement of the time taken for the kernel to hand off a packet to user space. Tests of 500 packets were performed and the average latency values were measured for the reference system and the simulated network containers running on top of the reference system. Results obtained, shown in Table 3.2, demonstrate that the average kernel latency of both systems is very similar with an average difference of 4.59% and very similar standard deviation values (σ).

3.6.2 Application Level Benchmarking

The *strace* tool [122] was used to measure the time taken at the application layer to execute network related tasks to eliminate application overhead as a potential disruptor of simulation performance. Specifically the *sendto*() Linux system call was measured to ensure that virtualisation level issues would not impact on the realism of simulations.

The execution of a simple UDP socket based streaming application was benchmarked. As can be seen from the results presented in Table 3.2 the LXC platform does not add an appreciable overhead, with an average difference in execution times of 1.63% and almost identical standard deviation values.

Table 3.2: Comparison of LXC and host network performance metrics

Test	**Real**	Std. Dev	**LXC**	Std Dev	**Difference**
Kernel Latency (μs)	26.714	1.54	25.541	1.79	4.59 %
strace Timings (ms)	22.87	2.52	23.25	2.71	1.63%
iperf ($Mbps$)	803.7	9.6	801.4	10.86	0.29%

3.6.3 iperf Benchmarking

For the purposes of automotive network simulation, the retransmission mechanisms of TCP are generally not useful, as ADAS rely on real time data. Thus UDP is a better fit. A performance analysis was carried out using the *iperf* tool [123] to analyse the performance of LXC containers under heavy UDP loads. As can be seen in Table 3.2, the containers show very similar performance to a real system and do not add any significant overhead.

A more detailed comparison of the performance of LXC versus other container based virtualisation techniques is contained in [114]. Although this work focuses on High Performance Computing applications, Xavier et al. found that LXC provided the best virtualisation performance across most benchmarks.

3.7 Summary and Conclusions

With modern advances in driver assistance and safety technology in vehicles, Ethernet is the obvious choice as the network backbone to support these high bandwidth applications. It is fast, inexpensive, flexible and ubiquitous.

In this chapter, a novel automotive network simulation platform is presented which uses a testbed approach to integrate real network traffic streams through lightweight virtual machines. Validation of the platform is presented using a number of tests designed to investigate the performance of the platform from the perspective of different network characteristics.

The presented platform allows the integration of real applications and network streams in a simulation environment transparently with the use of lightweight virtual machines. This gives an extra level of confidence that simulations carried out on potential network configurations will reflect real world conditions. One is not limited by the traffic generators available within a simulation platform, rather any real world application can be integrated into the network.

In the next chapter, testing is presented on two candidate automotive Ethernet topologies, namely *Double Star* and *Daisy Chain*.

The integration of high capacity communication networks within a vehicle enables the development and deployment of exciting, innovative and life saving safety applications. The introduction of Ethernet and the consolidation of the myriad of separate subsystems into a small number of powerful interconnected ECUs allows these applications to access more data, from more sources throughout the vehicle.

The development of a simulation testbed which integrates real traffic sources such as the platform presented in this chapter allows these algorithms to be tested on a variety of different network configurations quickly and without the overhead and expense required in building and testing prototype systems.

Chapter 4

Topology Testing Using Hybrid Testbed

4.1 Introduction

When designing automotive networks it can often be useful for engineers to test potential designs using a simulation platform rather than constructing a prototype network. This allows different topologies and network configurations to be quickly evaluated and tested. The effects of different network configurations can be observed by examining the difference in metrics such as End to End delay and packet delay variation. In the previous chapter, a Linux container based network simulation platform was presented. It is important that this testbed is evaluated such that its performance can be verified when simulating common automotive network topologies. This chapter does not propose new network topologies, rather it demonstrates the accuracy and capabilities of the presented platform for use in investigating automotive Ethernet network configurations.

In this chapter, the testbed described in Chapter 3 is used to investigate a number of network scenarios and topologies. The architecture of the two candidate next generation in-vehicle automotive network topolgies is presented, as well as the method of injection of camera traffic captured from a real vehicle optical camera system. A timing and scalability analysis of the platform is carried out in order to accurately evaluate the performance of the platform and discuss how data is collected from the testbed. The results of both 100 Mbps and 1 Gbps simulations are presented and benchmarked against those found in the literature and statistical analysis of the obtained results is shown, including CDF and Quantile-Quantile (QQ) plots. Finally conclusions drawn from the results are given.

4.2 Network Architecture

A discussion of the evolution of Ethernet based in-vehicle networks in the literature has already been presented in previous chapters, notably in Section 2.3 and Section 3.3 and therefore related work in this area will not be further discussed here.

The design of this automotive simulator gives a valuable advantage over other approaches in the literature when designing automotive applications. Applications can be run unmodified on Linux containers without rewriting or modifying code, or converting the applications into models compatible with the network simulation platform. This allows applications with complex or heavily varying network traffic profiles to be tested accurately. An example of such a traffic profile can be seen in the automotive H.264 videos used in this work. A graph of the variability of frame size of four of these videos can be seen in Figure 4.1. In these samples the frame size can be seen to be getting smaller at the end of the videos. This is due to the vehicle stopping which allows the H264 encoder to compress the frames more efficiently. The large spikes visible in the graph correspond to H264 keyframes which are inserted every 10 seconds by the encoder.

A topology diagram of the tested network architectures is shown in Figure 4.2 and includes video sources, control data, a radar device for ADAS as well as infotainment and generic internet sources. These topologies are referred to as *Double Star* and *Daisy Chain*, in line with conventions in the literature [81][46]. These topologies were chosen for this work as they represent the most common intra-vehicle topologies found in the literature.

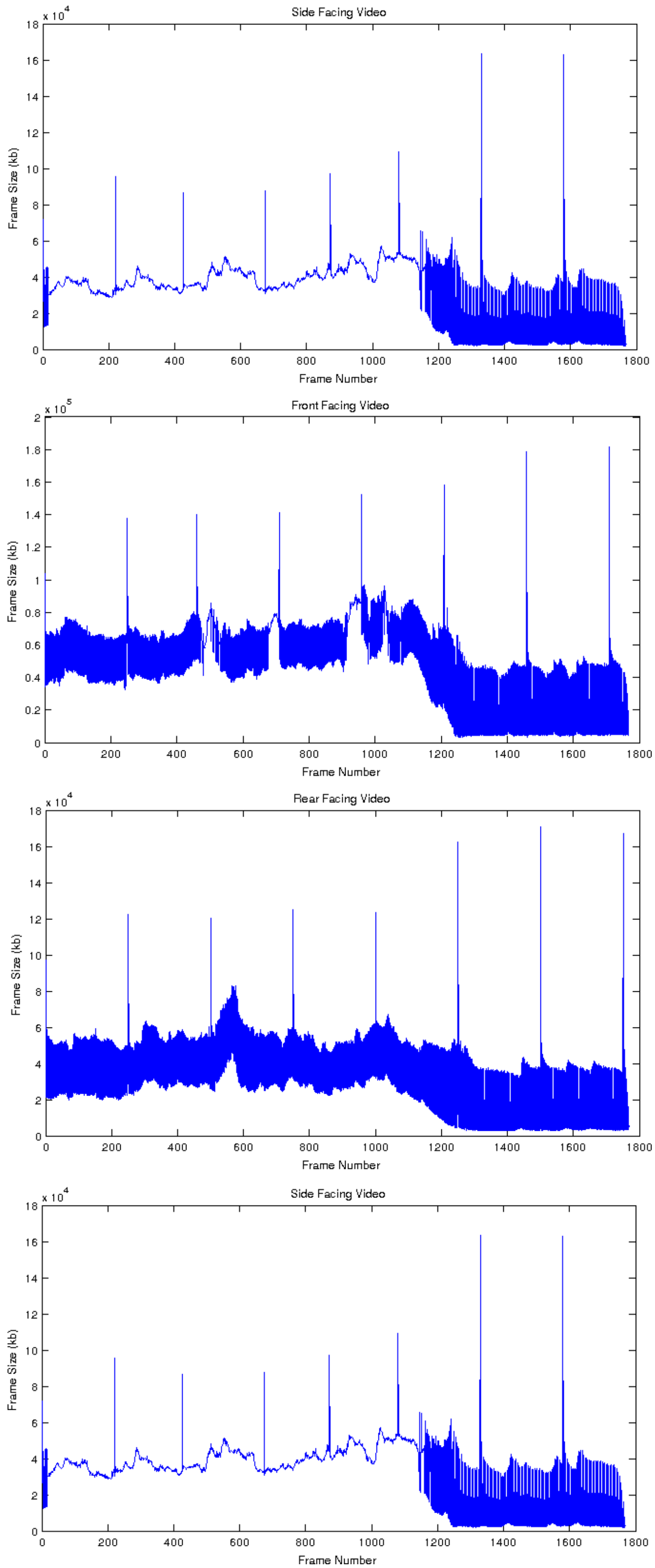


Figure 4.1: Bitrate Variability of Some H.264 Video Samples Used

4.2.1 Camera Traffic

Camera traffic is introduced to the network through Linux containers as described in Figure 3.3. The streams are created from video data captured offline from a real world automotive capture system and are transmitted onto the network using Real-time Transport Protocol (RTP) streams.

Video sources are uncompressed, 720 pixel x 480 pixel, 24 bits per pixel, 30 frames per second, real world automotive video. This gives a raw bandwidth of 248.83 Mbps (31.1 MBytes/s) using (4.1). These raw video sources were then encoded to 25 frames per second, H.264 format in real time as they are transmitted onto the simulated network, resulting in the bandwidth per video stream shown in Table 4.1. The method of capture of the video samples is discussed in more detail in Appendix A.1.

Table 4.1: Video Bandwidth

Link Capacity	**100 Mbps**
Normal Load	7.1 Mbps (H.264)
Heavy Load	10.1 Mbps (H.264)

$$
\begin{aligned}
Bandwidth &= (Width)(Height)(FPS)(Bits\ Per\ Pixel) \\
&= (720)(480)(30)(24) \\
&= 248.83 \text{ Mbps} \\
&= 31.10 \text{ MBytes/s} \qquad (4.1)
\end{aligned}
$$

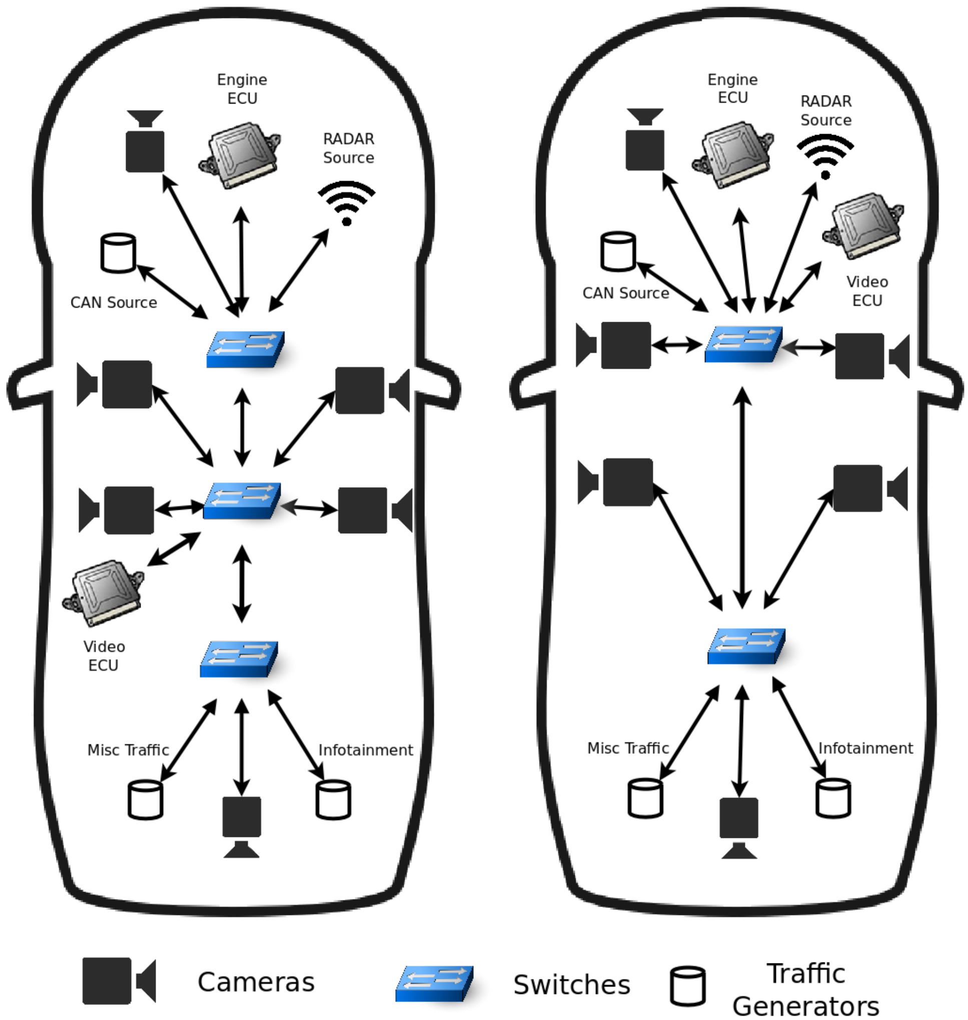


Figure 4.2: Tested Network Architectures containing cameras, radar, infotainment and CAN sources as well as receiver ECU devices.
Left - Daisy Chain topology. **Right** - Double Star topology.

Multi-camera systems such as that shown in Figure 4.2 have a number of uses, both passive (providing information to the driver) and active (causing an ADAS to potentially intervene in a dangerous situation). The integration and testing of specific algorithms is outside the scope of this work. Examples of camera based ADAS that are becoming more common on vehicles are:

- A front facing camera is used in lane departure detection as well as object and pedestrian detection. If the camera is sensitive to infra-red light, it can also enable night time pedestrian detection [34].
- Two fisheye cameras mounted on either side of the vehicle, above the wheel arches, are used when emerging from blind intersections. Object detection algorithms can be used to automate the detection of potentially dangerous situations using these two cameras such as detecting crossing traffic at an intersection or vulnerable road users (such as pedestrians or cyclists) at blind junctions.
- Rear mounted, often referred to as reversing cameras, are rapidly becoming a standard feature on even low end vehicles. The rear view camera is also used in conjunction with cameras mounted on the side mirror and front facing camera when generating the top view as shown in Figure 3.1.
- Two cameras are mounted on the side mirrors of the vehicle, pointing downwards towards the road surface. They are used in conjunction with the front

and rear cameras to provide a top down or birds eye view of the car to aid in parking situations. An example of this type of system is shown in Figure 3.1 with Inverse Perspective Mapping [2] typically used to generate this type of view.

4.2.2 Assumptions

In the configuration of the network testbed, the following assumptions are made:

- A network stack delay of 25μs is added to those streams which are not introduced to the simulated network using Linux containers, which is in line with the measurements from Table 3.2.
- A switch fabric delay of $5\mu s$ is added to each switch in the network. This represents an reasonable approximation of the switch fabric time based on manufacturer specifications of several commercially available Gigabit Ethernet switches. This value was chose due to the absence of readily available data on automotive Ethernet switches. It is in excess of value of $3\mu s$ which is found in Lim et al. [56] and Lee et al. [51].
- Drop tail queues of 1000 packets in depth are installed on each switch. This is the same size of queue used in similar experimental networks of this type such as Lim et al. [60], and reflects the memory specifications of commercially available equipment. The scope of this work does not include an examination

Table 4.2: Network Traffic Summary

Traffic Type	**Bandwidth(Mbps)**	**Packet Size (Bytes)**
Camera	*See Table 4.1*	
CAN	0.5	20
Radar	10	1472
Infotainment	10	1374
Misc TCP	15	Varies

of the effects of AVB or similar mechanisms on an automotive network.

- All camera streams are transmitted using UDP. These network streams contain safety critical information and the rebroadcast of lost frames, as used in TCP, is of limited usefulness.

- Infotainment traffic is also transmitted using UDP. Traffic in the *Miscellaneous Traffic* class, which represents internet traffic, is carried on TCP streams.

A summary of the traffic types on the network is contained in Table 4.2.

4.3 Timing and Scalability Analysis

When simulating events with a network simulator, timing is not usually a problem. Often in complex simulations, the simulator will take longer to carry out a task than that task would take in real time. However this is not an issue as statistics and measurements taken from the simulation are relative to the simulator clock and not relative to real time and are thus accurate with respect to each other.

However, when integrating both simulation and virtualisation, this is an issue, since a virtual machine works in real time, simulation delays can cause time dilation, which means that the arrival of packets at a receiver device appears to be delayed and therefore can disrupt the performance of applications running on the receiver.

This issue is dealt with in the testbed in a number of ways. The simulation platform integrates a real time scheduler which can operate using two scheduling methods : Best Effort and Hard Limit. When using the Best Effort scheduling method, if events cannot be served in real time and time dilation occurs, they are stored in RAM and addressed when possible. For this reason, it is possible for simulator time to fall out of synchronisation with the host time. When using the Hard Limit scheduler, if the simulator time falls out of sync with the host time by a small definable amount, the simulation will abort.

In the testbed, two operating modes were used depending on the required output; these modes are called **Measurement Mode** and **Real Time Mode**.

- Measurement Mode

  In this mode, the Best Effort mode of operation is employed. This means that the simulator time is free to run out of sync with simulated time. This means that extracting live data in real time, such as streaming video, is not possible as the receiving node will experience simulation delays. However, crucially, video can be input into the simulator reliably. It is cached until it can be processed. Also, delay and other important networking metrics are measured with respect to simulator time and are therefore accurate.

- Real Time Mode

  In this mode, Hard Limit real time synchronisation is used. This means that if the simulator clock drifts, the simulation will abort and therefore allows us to examine video, images and other data as they are processed through the simulation as though it were a physical network in real time. However, CPU limitations limit the possible bandwidth of simulated networks in this mode. These limitations will be explored in more detail in Section 4.3.1.

4.3.1 Scalability and Limitations

For the simulation results presented in Section 4.4, **Measurement Mode** was used. Since this allows the simulated clock to drift from real time, large complex high bandwidth networks are possible. The limiting factor for these types of simulation is RAM and, to a certain extent CPU, as traffic introduced from virtual containers is cached until the simulator can process them. For these simulations a 4th generation Intel Core i7 quad core processor with 8GB of RAM was used. This was more than sufficient to run the demonstrated network architecture, as well as 6 instances of the ffmpeg [124] real time video encoder running in Linux containers, which encoded raw video to H.264 and transmitted it onto the network. Logging components measure the time at which packets are received at each node within the simulation (relative to the simulation clock) and these values are used to calculate various network statistics.

In **Real Time Mode**, performance is limited by the CPU used. The network simulator must keep pace with the simulation and process simulation events in real time. This allows receivers to capture and display traffic transmitted through the network as though it were a physical network. As mentioned in Section 4.3, the simulator may deviate from real world time due to time dilation, that is, the simulation cannot "keep up" with real time. This means that a value must be chosen for how much the platform will be allowed to deviate from real world time; ideally this value would be as small as possible so that platform time tracks real world time as closely as possible.

In order to test the smallest possible stable value for this parameter, multiple simulations were run, changing the value each time in order to identify the optimum hard limit, which still allowed the simulation to execute. This value was measured to be 7.5ms. This is a large value relative to the maximum delay value required for control traffic as shown in Table 2.2 and, unfortunately, disqualifies the platform for real time streaming of control data; hence the focus in this work is to examine automotive video in the context of automotive Ethernet networks. This value could potentially be improved by taking advantage of a multithreaded architecture or more powerful server grade CPUs for processing packets. This would allow the platform to be used for real time streaming of control data. This value is topology independent; it is due to the initialisation of the LXC containers and their connection to the simulated architecture. This operation causes the simulation clock to deviate from real world time before returning to a smaller value. It is important to note that this limitation does not apply to **Measurement Mode** and therefore delay and other values can be measured from the simulation at the expense of being unable to receive video streams in real time.

To test the capabilities of **Real Time Mode** simulation, the iperf tool was used to measure the traffic level at which the simulator could process traffic in real time. The architecture shown in Figure 4.2 was used. The maximum traffic level between two virtual containers for which real time performance could be maintained with maximum time dilation of 7.5ms was found to be 50.3 Mbps of UDP traffic. This was validated in a second experiment by streaming two H.264 video streams between these containers in H.264 format of Constant Rate Factor of 2 and 1, resulting in a total bandwidth of approximately 50.3 Mbps. This may appear counter-intuitive, that the use of multiple streams would result in an identical value, however this is due to the fact that the value is entirely CPU bound. The platform operates using a single thread on a single CPU core and thus all packet processing must take place in this thread. When the thread runs out of resources, packets begin to be cached in RAM for processing in order when resources become free. However, in **Real Time Mode** this results in unacceptable time dilation levels in the system, far exceeding the limit of 7.5ms mentioned previously.

There are a number of options to improve this value. It could be increased if the maximum allowable time dilation is increased, at the expense of increased time dilation. Improved CPU technology would increase the Real Time packet processing ability of the platform. It is also possible to modify the simulator to run in a multithreaded fashion [125]. However, this approach was not used in this case due to concerns about synchronisation between the simulator and multiple LXC containers.

It is important to stress at this point that **Real Time Mode** as described above is only used when traffic is intended to be extracted from the simulation instantly and in real time, for example, to view automotive video streams in real time and examine network effects. Data such as delay and jitter values are collected from the platform in **Measurement Mode**.

4.4 Testing and Results

In order to rigorously test the performance of the network architectures, a suite of tests were performed. For each topology, two different load levels are defined to apply to the tested network architectures in order to test the performance of the network testbed. Load levels have been chosen in order to test the network simulation up to and beyond "breaking point". Load is increased by increasing the bandwidth of video introduced via camera streams.

When mixing virtualised and simulated hosts, the non-deterministic nature of the kernel could potentially lead to different experimental runs giving different results. However, it was found that this was not the case. The fact that both the virtualised hosts and simulation code use the same kernel and therefore the same scheduler meant that results remained consistent across experimental runs. Each scenario was simulated 50 times for 1000 seconds and the results from each simulation collated together to provide reliable and comprehensive results.

The bandwidth of the videos was set by the H.264 encoder to be 10 Mbps (High Load) and 7 Mbps (Normal Load), total measured bandwidth figures for each load level can be seen in Table 4.3.

Table 4.3: Total Bandwidth of All Sources

Normal Load	79.402 Mbps
High Load	97.102 Mbps

4.4.1 End to End Delay Measurements

End to End delay of each individual Ethernet packet was measured on the network and performance was benchmarked against the requirements detailed in Table 2.2. Maximum End to End Delay values for all traffic types and scenarios are contained in Tables 4.4 and 4.5. While control traffic exists on the network, results have not been presented for control traffic, as this work has focused on video traffic.

Figures 4.3 and 4.4 compare the CDF of End to End delay for video streams achieved under Normal and High Load conditions respectively. In Figure 4.3 it can be seen that both topologies meet the maximum End to End delay requirement of 45 ms under **Normal Load**. For the **High Load** scenario, neither topology meets the requirements.

In the High Load scenario, the CDF shows that the delay values for both topologies are quite similar. This is due to how the cameras are positioned in both topologies. In the Daisy Chain topology, four cameras only need to traverse a single switch to reach the Video ECU node compared to three cameras in the Double Star topology. Congestion at the heavily loaded bottom (rear) switch in the Double Star topology means that, although the Double Star topology still performs better when maximum End to End delay values are examined, the difference is not as large as in the **Normal Load** scenario. It was found that under **Heavy Load** the delay advantage of having less switches in the Double Star topology is somewhat counteracted by congestion at the switches when compared with the **Normal Load** scenario.

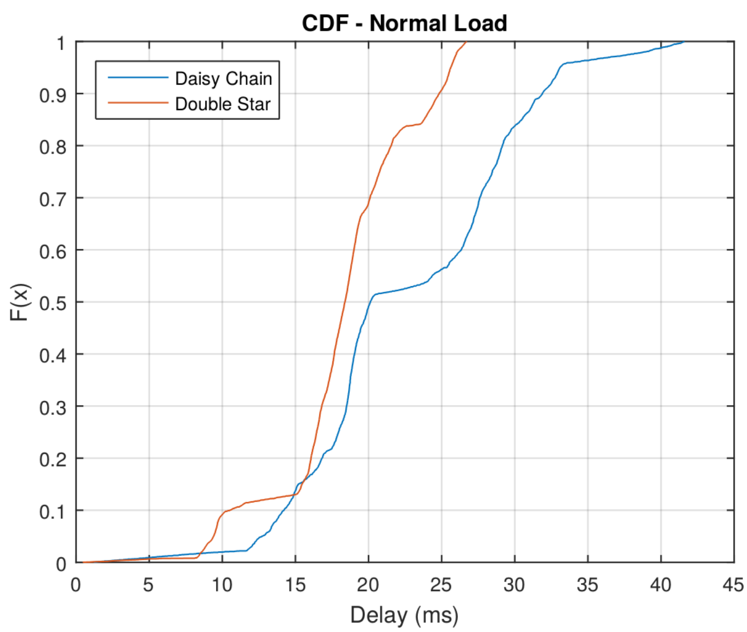


Figure 4.3: CDF of End to End Delay Measurements for **Normal Load** Scenario

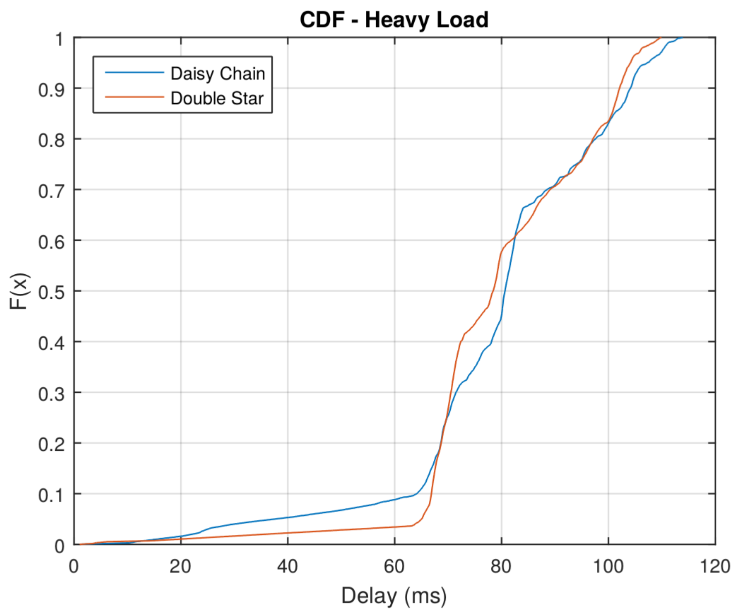


Figure 4.4: CDF of End to End Delay Measurements for **Heavy Load** Scenario

Table 4.4: Double Star Topology: 100 Mbps Maximum End to End Delay Values

	Video	**Infotainment**	**TCP**
Normal Load	30.29ms	26.67ms	28.28ms
High Load	106.31ms	106.32ms	401.64ms

Table 4.5: Daisy Chain Topology: 100 Mbps Maximum End to End Delay Values

	Video	**Infotainment**	**TCP**
Normal Load	41.69ms	48.25ms	42.72ms
High Load	114.66ms	128.79ms	652.9ms

The delay values observed under **Normal Load** are quite similar to those observed in [60] which models a similar *Double Star* topology. Comparing topologies, it can be seen that the *Double Star* topology has a smaller maximum delay value and outperforms the *Daisy Chain* topology. Though the difference between the two is slight, it is consistent across both Normal and High load conditions. This validates the results obtained in [46] which also found that a *Double Star* topology outperforms a *Daisy Chain* topology.

4.4.2 Packet Delay Variation (PDV)

For the purposes of evaluating the smoothness of traffic streams on the network, the PDV of the received packets is calculated. This is a term that can be defined in a number of ways so here it is defined as the average variation in delay values between successive packets (Equation 4.2). This definition is in agreement with that in IETF

Table 4.6: Double Star : 100 Mbps Average PDV Values and Standard Deviations (σ)

	Video	σ	**Infotainment**	σ	**TCP**	σ
Normal Load	0.117ms	*0.10ms*	0.136ms	*0.096ms*	0.667ms	*0.460 ms*
High Load	0.145ms	*0.151ms*	0.177ms	*0.112ms*	2.02ms	*7.5ms*

Table 4.7: Daisy Chain : 100 Mbps Average PDV Values and Standard Deviations (σ)

	Video	σ	**Infotainment**	σ	**TCP**	σ
Normal Load	0.114ms	*0.101ms*	0.193ms	*0.14ms*	0.764ms	*0.467ms*
High Load	0.139ms	*0.127ms*	0.259ms	*0.153ms*	6.38ms	*20.4ms*

RFC 3393 [126]:

$$PDV = \{Delay[P_n] - Delay[P_n - 1]\} \tag{4.2}$$

Average PDV values for video streams can be seen in Tables 4.6 and 4.7. PDV for Control traffic is negligible and is left out of this table. As expected, PDV values are larger when the network is much more heavily loaded.

PDV values for the Daisy Chain topology are higher than those for the Double Star topology on average (with the exception of those for video data, which are very similar). This is expected as there is an extra switch in the network which adds processing time for each packet as it traverses the network.

It is also clear that increased load on the network has a detrimental effect on jitter times. This is also demonstrated by increases in standard deviations (σ).

In network design, it can be very useful to know the distribution of PDV values for a particular network configuration. This allows for a network to better respond to PDV characteristics, for example, by providing adequate delay handling techniques and buffers. In order to investigate the distribution of the PDV data collected from simulations, QQ plotting was used. QQ plots are used to assess visually if a data set conforms to a particular probability distribution. A number of potential distributions were tested and those that provided the best fit were selected and are shown in Figures 4.5 and 4.6.

The QQ plots shown in Figures 4.5 and 4.6 provide an excellent fit for the data sets they represent, with the data conforming well to a Gamma distribution. PDV values conforming to a Gamma distribution is not uncommon and can be seen, for example, in Voice Over IP traffic in [127].

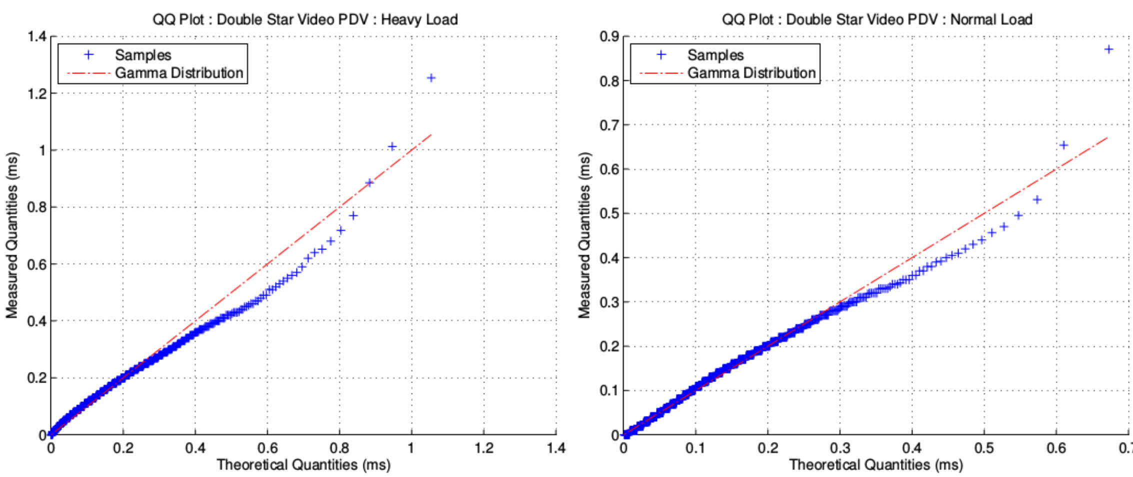


Figure 4.5: QQ Plot of Double Star Video Stream PDV values versus Gamma Distribution Under **Heavy** and **Normal** Loads

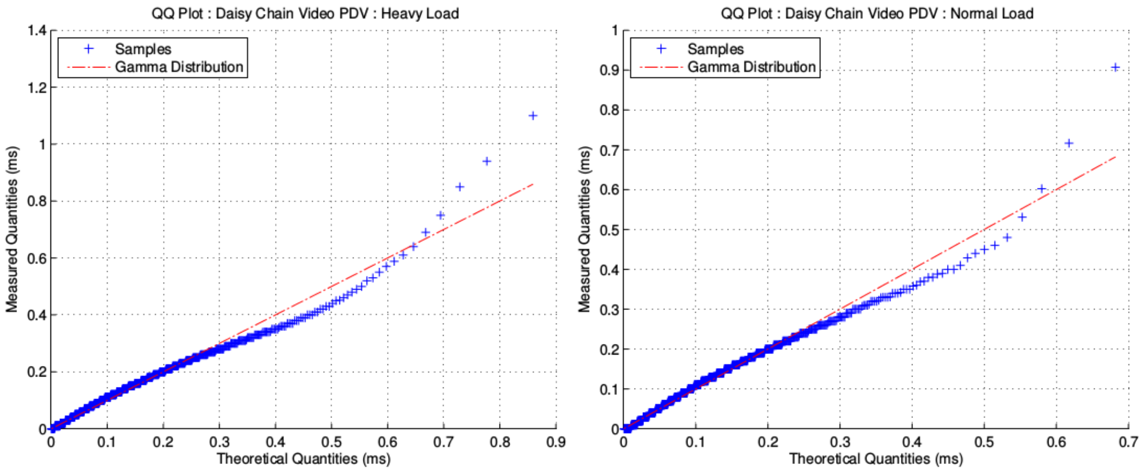


Figure 4.6: QQ Plot of Daisy Chain Video Stream PDV values versus Gamma Distribution Under **Heavy** and **Normal** Loads

4.4.3 1 Gbps Ethernet Investigations

While the automotive industry is currently focusing on 100 Mbps Ethernet implementations, the existence of the IEEE 802.3bp standard as mentioned in Section 2.7 shows that the industry is looking ahead towards Gigabit implementations of in-vehicle Ethernet. Gigabit Ethernet, while expensive at the moment, offers many advantages. Increased bandwidth naturally increases the potential for more advanced automotive applications and sensors. Increased numbers of cameras can be utilised to provide an improved view of the surroundings of a vehicle and improve ADAS.

Gigabit Ethernet provides the possibility of streaming raw video footage directly captured from the camera. Though the bandwidth requirements for raw video are extremely high, as shown in Equation 4.1, streaming raw video would eliminate the need for compression and encoding at the camera. This has the potential to decrease the time taken between image capture and processing. It would also eliminate the requirement for high powered video processing hardware in the camera itself.

With this in mind, the double star network simulation configuration detailed in Figure 4.2 was modified so that the links utilised were capable of carrying 1000 Mbps. Raw automotive video streams at a bandwidth of 248 Mbps were substituted for the H.264 video streams used in previous simulations. Due to the number of cameras employed, the bandwidth on some links would exceed 1000 Mbps, in these cases two simulated 1000 Mbps links were used.

Just as in simulations involving 100 Mbps links, two scenarios were tested: **Normal** and **High Load**. In this case, **High Load** represents all 6 cameras streaming raw video simultaneously while **Normal Load** includes 4 cameras operating. It is common for certain ADAS applications to utilise only a subset of the available cameras in a vehicle. When combined with other network streams such as Infotainment traffic and other sources described in Table 4.2, this results in a total bandwidth in the system of 1528 Mbps for **High Load** and 1031 Mbps for the **Normal Load** scenario. These figures are presented in Table 4.8.

Maximum End to End delay results are shown in Table 4.9. The maximum delay figures are much smaller than those shown for 100 Mbps simulations. This is due to the use of two 1000 Mbps links in these simulations to cater for the extremely high bandwidth generated by raw video streams.

Table 4.8: Total Bandwidth of All Sources in 1 Gbps Configuration

Normal Load	1031 Mbps
High Load	1523 Mbps

Table 4.9: 1000 Mbps Maximum End to End Delay Values

	Video	**Infotainment**	**TCP**
Normal Load	0.35ms	0.05ms	0.04ms
High Load	1.57ms	0.74ms	2.04ms

4.5 Summary and Conclusions

In this chapter a number of investigations into the performance and capabilities of a novel in-vehicle network simulation testbed are presented.

An analysis of the scalability and timing features of the testbed introduced in Chapter 3 is presented including details on how time dilation is addressed while carrying out simulations which mix virtual machines and simulated nodes. The maximum performance of the platform is investigated and information is given that would improve this performance by identifying bottlenecks which are present in the system.

Two common automotive Ethernet topologies are evaluated and End to End delay values as well as packet delay variation results are shown. Statistical analysis of these results is also presented. It was demonstrated that under severe load, in this case six in-vehicle cameras broadcasting simultaneously, along with control, infotainment and miscellaneous traffic, delay requirements for safety critical video information may be violated. The results obtained are shown to be in line with those in the literature.

Finally investigations into the use of Gigabit Ethernet are presented, while these may currently be too expensive for inclusion in vehicles by manufacturers, the standardisation of IEEE 802.3bp demonstrates that the industry is moving forward with Gigabit networks in mind. Simulations carried out demonstrate that the presented platform is suitable for the simulation of even extremely high bandwidth networks such as these.

The data and experiments presented in this chapter help to validate the testbed as an accurate and useful resource in the evaluation of Ethernet based automotive networks. In the next chapter, the platform is used in to conduct automotive specific subjective image quality experiments for packet loss effected videos, which further demonstrates its utility as a tool to help in the design and evaluation of automotive networks and associated video based applications.

Chapter 5

Image Quality Investigations Using Hybrid Testbed

5.1 Introduction

Vision systems are becoming increasingly prevalent in ADAS such as pedestrian detection and parking assistance [102]. Therefore video quality is extremely important since images displayed to the driver can be safety critical. Vision-based ADAS require significantly more bandwidth than traditional control applications as illustrated in Figure 3.1, thereby creating a challenge for automotive service providers to maintain these high quality video services. Network impairments such as packet losses and jitter can degrade video quality and negatively influence both the performance/reliability of ADAS and the Quality of Experience (QoE) of the end user. It is therefore of significant interest to automotive researchers to evaluate the quality impact of network impairments on visual quality and to develop models which predict the quality of a video stream in real-time. Such models enable automotive vision providers to guarantee a particular quality of service for safety critical video streams, for example, by prioritising bandwidth resources in the event of deteriorating quality.

Video quality measurements fall into two general categories, subjective and objective. Subjective tests involve surveying humans subjective opinion. Objective metrics evaluate some characteristic properties of a sample and can generally be computer automated. While many objective image quality metrics attempt to model human perception, in order to reliably assess image quality subjective tests are necessary, wherein a large number of viewers rate the quality of a number of test video sequences. Typically, the quality is rated on a 5 to 9 point scale, and the average score for each video sequence, termed the MOS is employed as the perceptual quality rating for a sequence [128]. Subjective tests are both time consuming and expensive and cannot be incorporated into real-time systems. As a result, a significant amount of research has been undertaken to derive objective quality metrics which reliably predict perceived image and video quality. Traditionally, Peak Signal to Noise Ratio (PSNR) has been used to evaluate perceptual quality [129], however more recent approaches, such as the Structural SIMilarity index (SSIM) of Wang and Bovik [130] have incorporated models of the human visual system to achieve closer correlation with subjective opinion.

In typical automotive in-vehicle networks, video quality can be degraded due to network related artefacts such as packet losses. However, the influence of such impairments on the QoE of the driver is not well understood. The QoE concept for automotive video differs substantially from the more traditional QoE concept for broadcasting since, in the automotive environment, the subjective satisfaction of the user is related to completing a particular task [131]. Other factors which may alter viewers perception of quality in the automotive environment include the use of High Dynamic Range (HDR) imaging and fish-eye lenses, which introduce radial distortion into the video sequence.

In order to carry out image quality measurement it is necessary to generate impaired video samples to show to subjects. In order to create the samples required for an automotive specific subjective test, it was decided to use the network simulation testbed detailed in Chaper 3. The simulation platform provides an automotive specific network configuration with all sources of traffic within an in-vehicle network included and also allows for the artificial introduction of a number of network impairments in a dynamic and flexible way. The platform also allows for the potential generation of live video samples which enter the network and are displayed in real time to a subject if required. Thus the simulation testbed provides a flexible platform for the generation of samples for automotive specific subjective tests. In this chapter, an automotive specific video quality database is created by collecting real video data from an in-vehicle rear-view driver assistance system and subjecting the reference video sequences to varying degrees of packet losses in order to model a noisy automotive environment. The impact of network induced impairments on the drivers perception of video quality is then assessed by conducting a subjective test. Saliency data is collected from each viewer to further assess the influence of packet losses on visual attention. It is demonstrated that the visibility of packet losses must be taken into account in order to accurately assess perceptual video quality. A general framework for modelling the perceptual quality of automotive video corrupted by packet losses is then proposed, which takes both temporal and spatial masking effects into account.

In this chapter the state-of-the-art in objective image and video quality assessment is presented. The details of the network simulation configuration used in this work is described, as well as the subjective test methodology and eye-tracking apparatus used in the experiments. The results of a 26 subject subjective test is presented and a no-reference framework for perceptual video quality assessment in the automotive environment is proposed. The results show that the developed framework correlates well with ground truth MOS, outperforming full reference metrics such as PSNR and SSIM.

5.2 Related Work

5.2.1 Objective Image and Video Quality

Image and video quality metrics can be broadly classified into two categories. These are full and no reference metrics. Full reference metrics make use of a reference image which is assumed to be of perfect visual quality. Traditionally, PSNR has been used to measure image quality since it is easy to compute and represents the energy in the error signal between a reference and degraded video frame. The prediction performance of PSNR is limited however, because it assumes that degradation in the video frame is only caused by signal independent additive noise. This assumption is not valid for packet loss degraded video and hence correlation between PSNR and subjective video quality is unreliable [129].

Full-reference image quality metrics such as the Multi-Level Similarity Index (MLSIM) of Zhang et al. [132], Visual Signal to Noise Ratio (VSNR) of Chandler and Hemani [133], and Information content Weighted Structural SIMilarity (IW-SSIM) index of Wang and Li [134] represent the state-of-the-art in terms of correlation with human opinion scores and have many applications in image quality assessment.

In recent years, the effect of distortions on video quality has been analysed in great detail and many full reference models have been proposed. For example in [135], the authors presented an approach for deriving a QoE model for different patterns of packet losses in high definition video streaming. The authors used the SSIM of Wang et al. [130] together with temporal pooling techniques and content characteristics to derive their quality model. In [136], the authors considered the effects of burst losses and correlation between error frames in a model dedicated to low bit-rate H.264/AVC video, while in [137], Seshadrinathan et al. demonstrated that by utilizing a model of temporal motion through the use of optical flow vectors, temporal artifacts in video sequences can be incorporated into objective quality models to improve prediction performance.

Visual saliency refers to the parts of an image or view that attract a viewers attention. It is often useful to understand visual saliency in image quality measurement as issues in the more salient parts of an image are generally more apparent to a subject than those which occur outside of the salient area. The use of visual saliency has been investigated in several full reference metrics, for example, in [138], the authors show that by applying a saliency model to two existing video quality metrics, their prediction performance can be improved considerably. Feng et al. [139] used Itti's saliency detection method [140] to derive two models for video quality assessment. In the first model, Itti's saliency model was incorporated into the pooling strategy, weighting salient pixels more heavily than non-salient pixels. The second model is based on the hypothesis that human attention changes due to packet loss induced spatial-temporal artifacts. The authors measured deviations in the saliency maps of reference and distorted videos to derive a quality model. The validity of the above hypothesis for automotive video is questionable however, since the obtained results, based on eye-tracking saliency data show no such deviations in visual attention due to packet losses. In [141], Lin et al. proposed a generalized linear model for video packet loss visibility that is applicable to different group-of-picture structures. The authors applied a visibility model to packet loss prioritization, enabling routers to intelligently drop packets in order to minimize their impact on visual quality.

In the automotive environment, objective video quality metrics aim to automatically evaluate the perceived quality of a video, so that a guaranteed level of service can be achieved, for example, by reallocating system resources should a drop in quality occur. However, in the automotive environment a reference image is typically unavailable. No-reference (NR) quality metrics attempt to assess perceptual quality without access to a reference image. This is a much more difficult task than full-reference quality evaluation and until recently the majority of no-reference metrics have been distortion specific. For example, there are many algorithms that rate the quality of blurred [142, 143, 144] or compressed images [145, 146, 147]. Recently, distortion-independent approaches have been proposed [148, 149] which are based on the statistical properties of natural images. Natural images exhibit regular statistical properties that are altered by the presence of distortions [150]. These regular properties are referred to as Natural Scene Statistics (NSS) and deviations from these statistics can be quantified to predict perceptual image quality. In [151], the DIIVINE index models the NSS of wavelet coefficients. These wavelet coefficients are used to identify the most likely distortion type, followed by distortion specific quality assessment. A similar approach called BLIINDS-II is described in [148] which operates in the Discrete Cosine Transform (DCT) domain. A small number of features are computed from an NSS model of block DCT coefficients. These features are then used to train a regression model which accurately predicts perceived image quality. An adaptation of this algorithm was proposed in [152], which operates on video sequences.

The majority of no-reference image quality metrics mentioned above operate over local image patches and incorporate some form of spatial pooling strategy to derive a single quality score. In the case of global distortions such as Gaussian noise, blur or blocking artifacts associated with image compression, such metrics have been shown to correlate well with perceptual quality. For global distortions, image impairments are present in most, if not all of the image patches on which quality is computed. In the case of more localised impairments such as packet losses, the above image quality metrics may not accurately predict image quality. For example, in a recent study [153], the Pearson correlations of the PSNR and SSIM index with subjective opinion scores for video sequences transmitted through error-prone IP networks were only 0.4108 and 0.5119 respectively.

No-reference metrics that assess quality impairments due to packet losses include [154], in which the authors presented three NR methods to estimate the Mean Squared Error (MSE) due to packet loss directly from the video bitstream. However, the impact of a viewer's QoE and attention was not studied in this work. These algorithms were subsequently utilized by Kanumuri et al. [155] to develop a NR method which incorporates a pooling strategy based on the visibility of packet losses. The visibility of packets was derived from a subjective test consisting of 1080 packet losses over 72 hours of video. In [156], the authors proposed a new analytical framework for evaluation of network parameters and MPEG-2 video sequences. Network parameters are used to characterize the packet loss pattern of an IP network. Meanwhile, in [157], a NR video quality model was derived based on continuous estimates of packet loss visibility. The proposed algorithm extracted a set of features from the video bit-stream and predicted the visibility of packet losses using support vector regression.

5.3 Network Simulation Methodology

When examining potential options for the generation of samples for use in subjective experiments, it was decided to make use of the simulation testbed platform explored in detail in Chapter 3. The use of this platform allowed for the preparation of packet loss impaired video. As already discussed, testbed simulation allows the insertion and extraction of real automotive video data from an advanced and accurate automotive network testbed containing traffic flows modelled on those found in real vehicles. The ability to extract packet loss degraded video from the simulation is key in this use case, as the video will be shown to real life subjects as part of a subjective test.

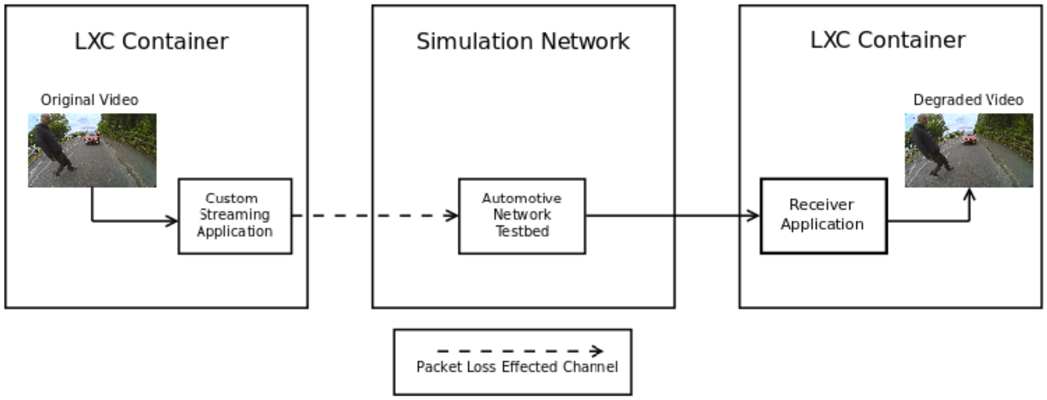


Figure 5.1: Illustration of flow of video through testbed

5.3.1 Video Streaming Mechanism

An illustration of the path of video through the network simulation is contained in Figure 5.1. Each input video consists of automotive video samples of 944 x 531 pixels at 25 frames per second captured from a vehicle equipped with four video cameras. These samples are input to a custom video streaming application developed specifically for this experiment. The application streams uncompressed video frames in real time into the automotive testbed platform using the UDP protocol.

5.3.2 Network Topology

A top down diagram of the network topology used in these simulations can be seen in Figure 5.2. The network models a triple star or daisy chain in-vehicle network, a topology which can be commonly found in the literature as a candidate topology for Ethernet based next generation networks [46] [81] [158]. The network contains

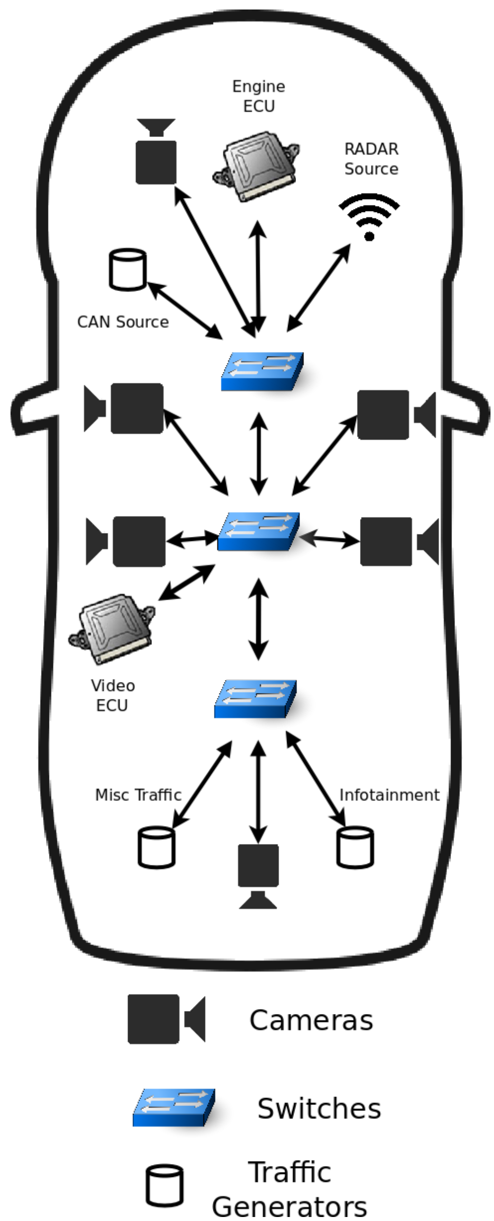


Figure 5.2: Network topology for generation of degraded video samples

the following devices:

- Optical Cameras

  The camera nodes in the network are attached to Linux containers, which use a custom built video streaming application to send source videos of resolution 944 x 531 pixels at 25 frames per second across the simulated network. These samples were captured from cameras in a real world vehicle on public roads.

  The samples were transmitted across the network uncompressed to avoid the introduction of compression artifacts to the samples as this may distort subjective test scoring.

- Infotainment and Miscellaneous Traffic

  For infotainment and misc. traffic (which could come from a 3G internet connection or wireless node within the vehicle), the flows are modelled as TCP streams.

- CAN Gateway

  The data rate of a CAN bus is limited by its length. Since a vehicle is a small space and CAN connections within are generally < 10m, a bit rate of 400 kbps is assumed. A frame size of 20 bytes is used, representing the maximum frame size allowable by the CAN bus standard.

- Radar Device

The Radar sensor device contained in the simulation outputs data across a FlexRay gateway at 10 Mbps.

5.3.3 Packet Loss and Recovery

Packet loss is introduced to video streams through the use of a mathematical error model on the simulated Ethernet links connecting the cameras to the video receiver node. This works by marking packets which pass through the link according to a mathematical model. Using a random number generator and a pre configured percentage value, packets are dropped in bursts such that the overall occurrence of dropped packets is based on a random distribution, but also has a predictable percentage.

Samples were transmitted through the network at 4 different levels of impairment/packet loss (P1-P4), to model video corruption due to the noisy automotive environment. On the receiver side, a repetition type insertion repair technique [159] is carried out on the received frames of video.

This is a technique whereby information from the most recent previous frame is retained and in the case of packet drops, those parts that are missing are inserted into the gaps in the new frame, providing a simple yet resource efficient packet loss mitigation technique.

While there exists a large number of different techniques for the mitigation of packet loss [160], such as interpolation, interleaving and retransmission, in an automotive scenario, the minimisation of delay between receipt of a frame and its display to the driver is extremely important. The repetition type insertion repair technique offers a combination of low computational cost, high speed and good subjective performance.

An example of a video frame extracted from the simulation having been subjected to 10 % bursty packet loss can be seen in Figure 5.3. Large levels of impairment result in 'blocky' sections where movement has taken place between frames, this is visually similar to the effects that are seen on other types of streaming video undergoing packet loss [160] [135].

Figure 5.3: Input and extracted output frame from simulation after undergoing 10 percent packet loss

5.4 Video Quality Experiments

The goal of the experiments was to evaluate the effect of packet loss on the quality of user experience for automotive applications. The particular application under test was a rear-facing camera automotive display system, normally utilized for parking assistance systems. As such, the reference video sequences used in the experiment were all of urban driving scenes captured from a fish-eye, in-vehicle rear-facing camera at a frame rate of 25fps and cropped to an aspect ratio of 16:9. The videos extracted from the network simulation testbed are referred to as Processed Video Sequences (PVSs). As described in Section 5.3, the simulation testbed [37] was used to model a multi-camera in-vehicle driver assistance system. This configuration facilitated the introduction of real network traffic to the simulation environment through the use of its Tap bridge functionality which is illustrated in Figure 5.4. The video was sent through the simulation environment under varying degrees of packet loss to generate the PVSs. Four levels of impairment (P1 - P4) were chosen to span a wide range of video quality. The percentages of packet loss for each level of impairment (P1 - P4) were 1, 2.5, 5 and 10 % respectively. Ten reference video sequences for the subjective test varying from 8 to 24 seconds in duration were used. The average duration of the reference videos was approximately 16 seconds.

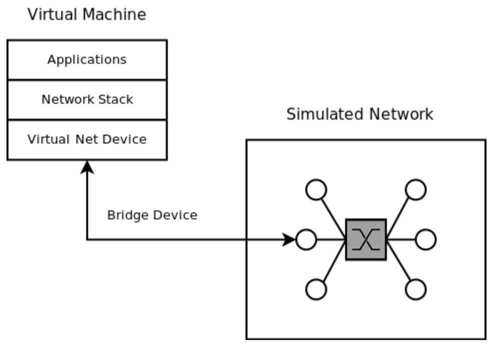


Figure 5.4: An illustration of the network architecture used for the introduction of packets into the simulated network

Sequences were chosen to evenly span a wide range of spatial and temporal activity as proposed in [161]. This enabled an evaluation of the effect of temporal and spatial masking effects on the visual attention of the viewer. The spatial perceptual information over the entire video (SI) is defined as:

$$SI = max_{frame}(std_{space}[sobel(F_n)]) \tag{5.1}$$

and the temporal perceptual information (TI) as:

$$TI = max_{frame}(std_{space}[F_n - F_{n-1}]) \tag{5.2}$$

Both SI and TI are combined according to Fenimore et al. [162] to determine the complexity of the scene:

$$SI(F_n) = rms_{space}[Sobel(F_n)] \tag{5.3}$$

$$TI(F_n) = rms_{space}[F_n - F_{n-1}] \tag{5.4}$$

Table 5.1: Characteristics of Reference Sequences

Video Sequence	SI	TI	Complexity
1	86.98	14.43	3.10
2	91.46	13.10	3.08
3	118.91	15.65	3.28
4	117.11	6.85	2.90
5	118.49	3.16	2.57
6	91.40	18.13	3.23
7	105.59	6.28	2.82
8	88.04	6.73	2.78
9	110.17	14.99	3.22
10	107.90	7.84	2.92

$$C = log_{10} \sum_{1}^{n} [SI(F_n) \times TI(F_n)]/n) \tag{5.5}$$

where, F_n is the luminance-only video frame at frame number n, Sobel [163] is the sobel filter, max_{frame} is the maximum value in the video sequence, and the std_{space} and rms_{space} are the standard deviation and root mean square over all pixels in a frame, respectively. The spatial and temporal perceptual information of the reference sequences used in the study are reported in Table 5.1 and Figure 5.5.

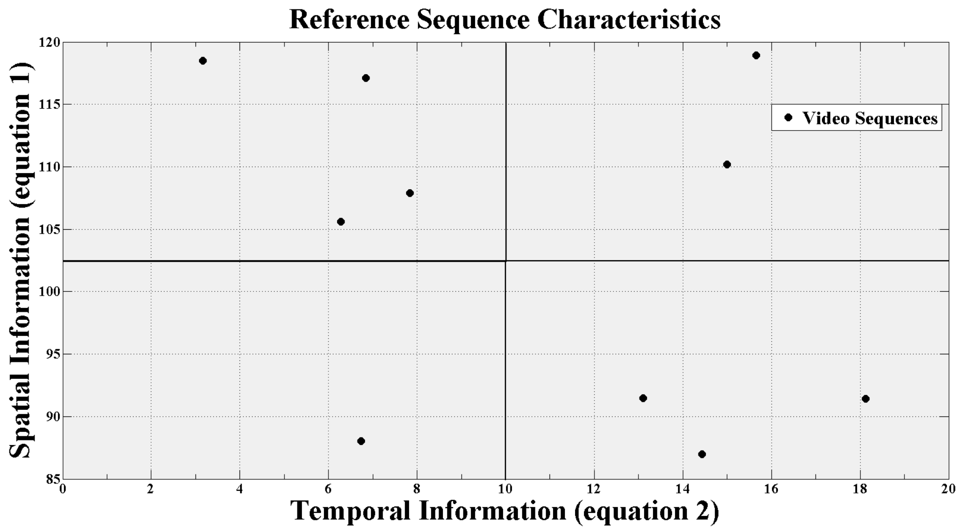


Figure 5.5: Reference sequences in the dataset were chosen to span a wide range of spatial and temporal complexity.

5.4.1 Subjective Test Methodology

In this section the subjective test experiment is described in detail. The subjective test was performed using the Absolute Category Rating-Hidden Reference (ACR-HR) method [128]. This method was chosen since typical automotive vision systems utilize fish-eye lenses with fields-of-view of up to 190 degrees [144]. These lenses offer a distinct advantage over rectilinear lenses since they allow the driver to see more objects approaching from the sides of the vehicle. However, fish-eye lenses introduce radial distortion to the image, wherein straight lines are mapped to curves. In the ACR-HR method, the reference videos are included somewhere in the subjective test, without being identified to the subject. The addition of the hidden references in the subjective test avoids the potential problem of reference images being given poor subjective scores due to radial distortion. Viewers therefore rate the reference images as they would any other test sequence. The quality scores are then reported as DMOS given by equation 5.6.

$$DMOS = MOS(original) - MOS(degraded) \tag{5.6}$$

The selected test methodology is derived from the ITU-T recommendation P.910 [128]. Only non-expert viewers as defined by [135] participated in the subjective tests. A total of 26 viewers undertook the study which involved a single session lasting approximately 25 minutes in order to minimize viewer fatigue (an after-study questionnaire indicated that viewers experienced little fatigue during the course of the study). Each study began with a short training session, during which the subjects were presented with video sequences chosen to span the range of impairments contained in the test data. The study consisted of 50 video sequences shown in random order. Furthermore, the order was randomized for each subject and care was taken to ensure that two consecutive sequences did not belong to the same reference sequence in order to minimize memory effects. Subjects were instructed to watch the entire sequence before voting, receiving on-screen instructions as to when to vote. Subjective ratings were reported on the five-point scale: ”Excellent”, ”Good”, ”Fair”, ”Poor”, and ”Bad” [128]. The study took place in a dedicated viewing room with low background illumination. Sequences were displayed on a 24 inch DELL ST2421L monitor with a screen resolution of 1920 by 1080, centered, at their original size of

944 by 531 pixels. The background screen illumination was mid-grey, conforming to recommendations [128]. The viewing distance was 70cm, or approximately 4 times the video height. A subject rejection procedure outlined in [164] was carried out which rejected one subject. The remaining scores were averaged across subjects to obtain the MOS for each video sequence.

5.4.2 Eyetracking Data

In order to track and record the viewers' eye movements, an Eyetribe tracker [165] was used. An image of the eye tracking device can be seen in Figure 5.6. Unlike many infrared eye-tracking systems, the Eyetribe tracker does not require the viewer to use a rigid head rest, rather the viewer must only be located within the tracker's trackbox, which is defined as the volume of space wherein the subject can be tracked by the system. Thus, the subjects' head movements were unrestricted for the duration of each subjective experiment, enabling a more realistic viewing environment. A 12 point calibration step was performed on each subject before beginning the test. The calibration step took less than one minute and ensured that the accuracy of the eye-tracking device was optimized for each subject. The pixel coordinates of each subjects' gaze fixation were recorded for every frame of video viewed in the experiment using a custom application which tagged each frame with the coordinates of the subjects gaze fixation. The technical specifications of the eye-tracker are listed in Table 5.2.

Table 5.2: Technical specifications of eye-tracker

Sampling Rate	60Hz mode
Accuracy	$0.5° - 1°$
Spatial Resolution	0.1°(RMS)
Latency	$<$ 20ms at 60Hz
Calibration	12 points
Operating range	45cm - 75cm
Tracking area	40cm x 30cm at 65m distance
Screen size	24”
Data output	Binocular gaze data

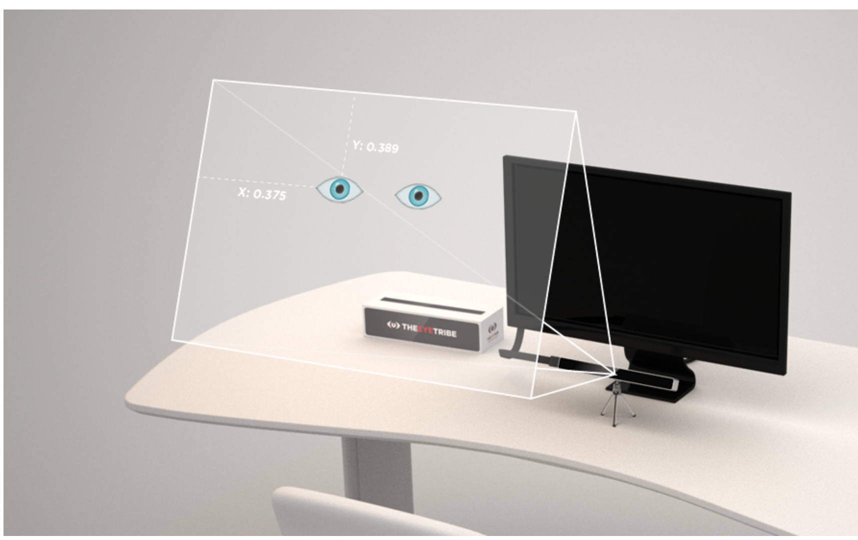


Figure 5.6: Eyetribe eye tracking device used for saliency data capture

5.4.3 Deriving a Saliency Map

A saliency map was derived from the spatial pattern of fixations in the eye tracking data according to [166]. Each subject's fixation location was recorded for each frame of video data yielding an average fixation map ($FM_{(x,y)}$) over all subjects. A Gaussian distribution, the width (σ) of which approximates the size of the fovea (approximately 2° of visual angle) was then applied to each fixation point (x, y) in FM to obtain a mean Saliency Map (SM):

$$SM(k,l) = \sum_{t=1}^{T} exp[-\frac{(x_t - k)^2 + (y_t - l)^2}{\sigma^2}] \tag{5.7}$$

where $SM(k,l)$ indicates the saliency map for each given pixel (k,l) where $k \in [1, M]$ and $l \in [1, N]$, T is the total number of fixations, $(x_t,\, y_t)$ are the spatial coordinates of the i^{th} fixation and σ is the standard deviation of the Gaussian distribution. The intensity of the resulting saliency map is linearly normalized to the range [0,1]. Figure 5.7 illustrates an example SM derived from eye-tracking data obtained from a hidden reference image and an SM of the same video frame corrupted with packet-loss level P4.

Figure 5.7: The saliency maps from a reference frame (left) and corresponding degraded frame (right).

5.5 Analysis of Subjective Results

In Figure 5.8, the DMOS scores are reported for each video sequence. Recall that the DMOS score is the difference between the reference and degraded MOS scores, hence a lower DMOS score represents a higher quality rating. It is observed that the decrease in perceptual quality with respect to increasing packet loss is largely monotonic, however there are a number of outliers which have significantly lower DMOS scores (higher perceptual quality ratings) than expected for the level of packet loss. In particular, the largest outlier (sequence 5) corresponds to the sequence with the lowest temporal difference between frames. The next two lowest DMOS scores also have low temporal differences between frames (sequences 7 and 10). These sequences contain many instances of packet loss that were not noticed by the viewers due to similarities in consecutive frames. These results highlight the need to consider packet loss visibility in order to adequately assess video quality.

One of the key issues in studying quality of perception is identifying factors which

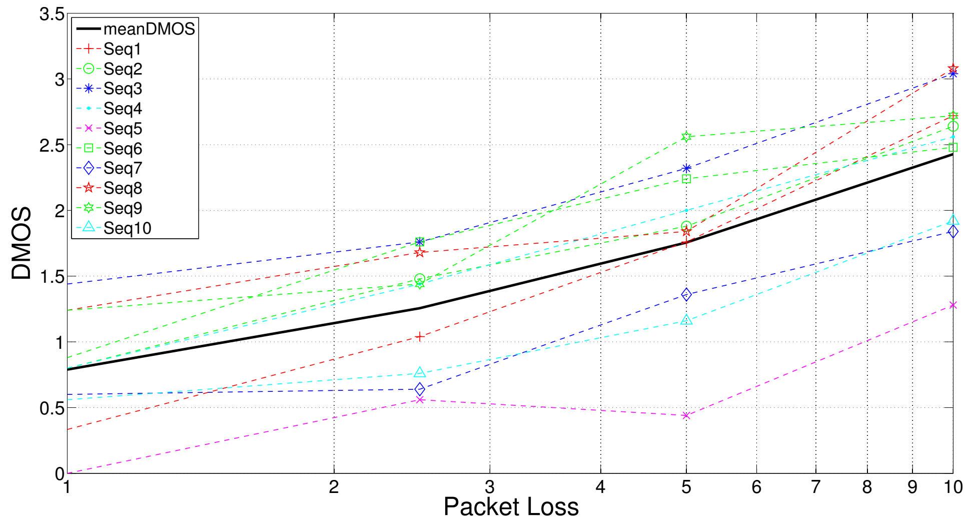


Figure 5.8: The DMOS scores from the subjective test, plotted on a log scale.

significantly alter visual deployment. The Area Under the Curve (AUC) is a commonly used indicator to compare saliency maps [167]. The AUC evaluates the area under the Receiver Operating Characteristic (ROC) which is found by plotting the false positive rate (the number of pixels incorrectly labelled salient in the degraded image) as a function of the true positive rate (the number of pixels labelled salient in both images). Given a reference saliency map SM_{ref} and degraded saliency map SM_{deg}, the ROC is derived from the number of pixels labelled as salient in SM_{ref} and SM_{deg}, versus the number of pixels labelled as salient in SM_{ref} which are not salient in SM_{deg}. A value of AUC $= 1$ indicates a perfect match, while a value of AUC $= 0.5$ indicates only a random match.

Eye tracking data and visual saliency are subject to high inter-observer variability [168]. Therefore, in order to fairly evaluate the influence of packet loss on human attention, it is necessary to calculate an AUC upper-bound taking inter-observer variability into account. To determine an upper bound on similarity between saliency maps, the procedure adopted in [168] was used to determine the . The Upper Empirical Similarity Limit (UESL) is derived as the maximum achievable similarity between the saliency maps derived from two groups of human observers under the same experimental conditions. For each reference video frame observed in the ACR-HR subjective experiment, subjects were divided into two randomly chosen groups; A and B, and their corresponding saliency maps SM_A and SM_B were calculated. The UESL was then computed as:

$$UESL = AUC(SM_A, SM_B) \tag{5.8}$$

The influence of packet loss on visual attention could then be defined by the normalised similarity (NS) which is the similarity between saliency maps obtained from both reference and degraded sequences divided by the UESL:

$$NS = AUC(SM_{ref}, SM_{deg})/UESL \tag{5.9}$$

The normalised similarity thus gives a measure of the similarity between saliency maps obtained from video sequences with different quality levels while taking inter-observer variability into account. Lower values of NS indicate lower similarity between saliency maps. It should be noted that because the limits are defined empirically, a value of NS greater than 1 is possible. The normalised similarity was calculated for every frame of every video sequence. Table 5.3 shows the average NS for each video sequence in the subjective tests. The results show that increasing the level of packet loss had almost no effect on visual attention, despite significant differences in the MOS scores of different levels of packet loss. This is an interesting result and points to the attention of the viewer being more strongly influenced by task related (also called top-down) factors, such as identifying potential dangers on the road, than so called "bottom-up" sensory cues which are more related to low-level vision. A study reported in [167] found similar results in a free viewing task. To investigate this result further, the frame by frame saliency data of each video sequence was examined. The results show that there is little difference in viewer attention between the reference and corrupted video sequences. Figures 5.10 and 5.9 illustrate this point. Figure 5.10 highlights the similarity between saliency maps from a reference and corresponding corrupted video sequence (with 10 percent packet loss). The normalised similarity between the corrupted and reference saliency maps of this sequence is 0.9044, despite the corrupted sequence having a DMOS score of over 2.5.

Table 5.3: Normalised Similarity of Degraded Saliency Maps

Sequence	P1	P2	P3	P4
1	0.8745	0.8686	0.8609	0.8706
2	0.9041	0.8876	0.9112	0.8944
3	0.8361	0.8543	0.8860	0.8667
4	0.8957	0.8806	0.9520	0.8766
5	0.9023	0.8949	0.9151	0.9192
6	0.8621	0.8678	0.8766	0.8468
7	0.8870	0.8974	0.9020	0.8593
8	0.8935	0.9029	0.9061	0.9183
9	0.8744	0.8763	0.8867	0.9044
10	0.8776	0.8859	0.8618	0.8821

Peaks in UESL values in Figure 5.10 represent video frames where there is low inter-observer variability. These frames correspond to Figure 5.9 (a) - (c), where there is a single pedestrian in the frame. On the other hand, troughs in the UESL values from Figure 5.10 correspond to frames (d) - (f) in Figure 5.9, which contain multiple pedestrians and vehicles. In general, the presence of pedestrians in a video sequence had the strongest influence on visual attention.

Figure 5.9: The frames with lowest inter-observer variability (a-c) correspond to frames with a single point of focus while frames with the highest inter-observer variability (d-f) contain multiple salient regions.

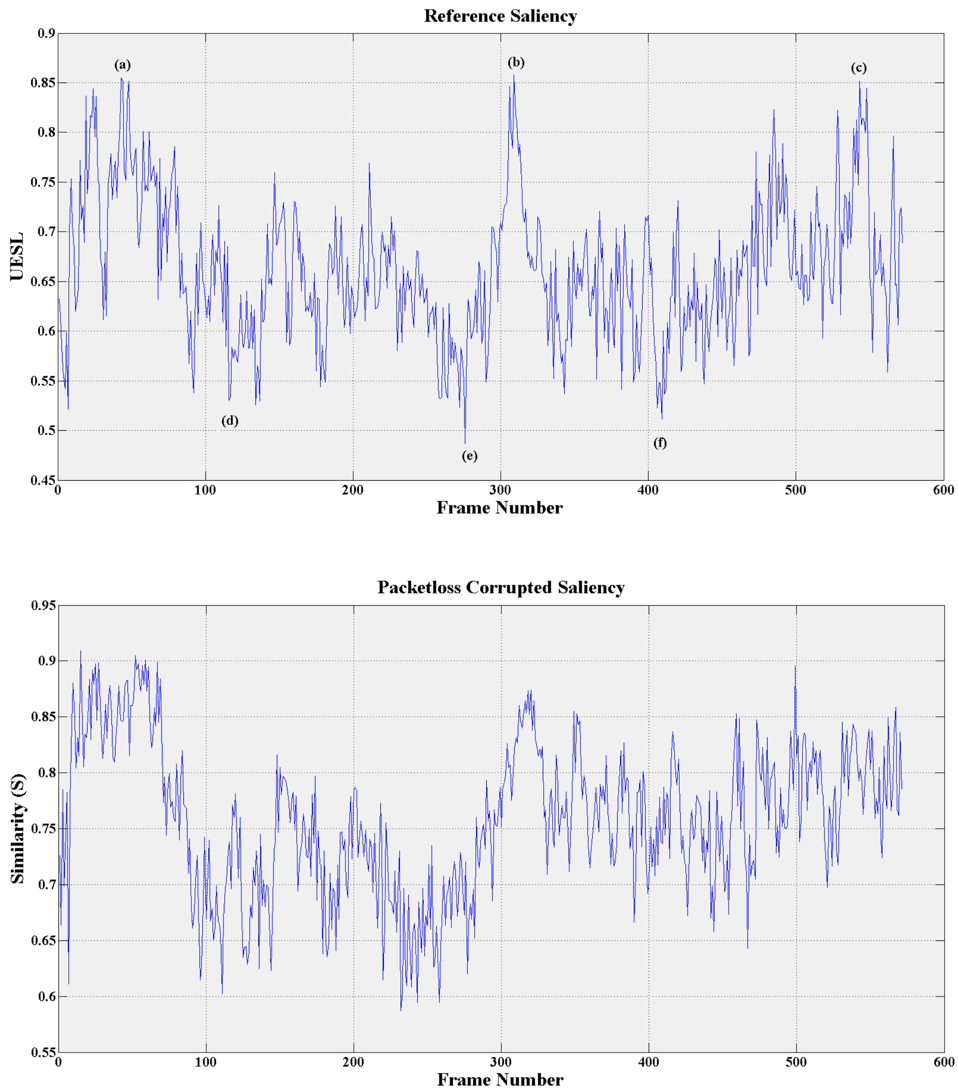


Figure 5.10: The normalised similarity (0.9044) of the saliency maps indicate that packet loss has little influence on visual attention, rather the content of the video determines the attention of the viewer.

5.6 No Reference Packet Loss Image Quality Metric

The packet loss degradation in the dataset is neither spatially nor temporally uniform. Some areas of the frame are degraded while the quality of other areas remains unchanged. Table 5.4 highlights the quality scores from three objective quality metrics for each video sequence. In the case of the PSNR and SSIM metrics, the mean score across the entire sequence is used. Both PSNR and SSIM are full reference metrics, however, even with the use of a reference image they do not correlate well with human opinion scores for this type of packet loss. In fact, the more recent no-reference video quality metric BLind Image Integrity Notator using DCT statistics proposed in [152] outperforms both full-reference algorithms. Nevertheless, the correlation with subjective MOS scores from the dataset remains poor. Quality prediction can be improved by deriving a model of perceptual quality which incorporates the saliency of packet losses.

Due to the packet loss recovery model used, (described in Sec. 5.3.3) the location of instances of packet loss could be determined by computing the correlation (inner

Table 5.4: Correlation of Quality metrics with MOS

PSNR	0.3580
SSIM	0.3794
Video BLIINDS	0.4240
Proposed Quality Model	0.8211

product) between consecutive frames. Spatial regions where packet reconstruction has occurred are identical to the previous frame and hence have a correlation of 1, while non-corrupted image patches always have a correlation of less than 1. This is the case even for stationary sequences since slight variations in pixel values occur due to sensor noise at image capture. Although the method of locating instances of packet loss is specific to this recovery algorithm, alternative packet loss recovery methods typically introduce characteristic distortions in the video frame that can be distinguished from an uncorrupted frame; hence the model can be incorporated into alternative recovery algorithms with minor modifications.

Having found instances of packet losses, the goal was to categorize each instance as either salient or non-salient. For each frame containing a packet loss, the temporal difference between it and the previous frame was calculated according to:

$$TI_{frame} = (std_{space}[F_n - F_{n-1}]) \tag{5.10}$$

It is hypothesised that packet losses are most salient if there is a large temporal difference between consecutive frames in the spatial region around a lost packet. Therefore, the temporal difference at the borders of each lost packet was measured. A border width of 10 pixels was chosen heuristically. Each local region around a lost packet was defined as salient only if the temporal information of that region exceeded a threshold of visibility chosen based on the Just Noticeable Difference (JND) values observed from the subjective experiments.

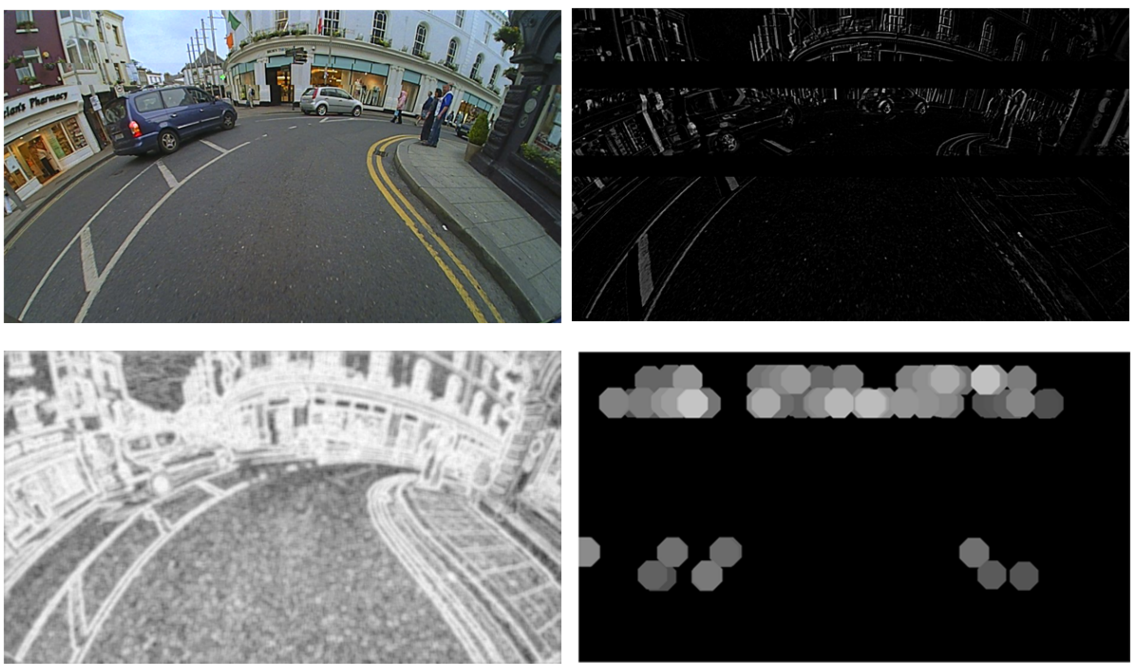
The spatial texture of the lost regions was also considered, since regions with high texture have been shown to mask image degradations [169]. The temporally salient packet loss regions were weighted by the spatial entropy, where the entropy of a probability density function $p(x)$ is defined as:

$$H = -\int p(x) \ln p(x) dx \tag{5.11}$$

Entropy (H) is a statistical measure of randomness that has been widely used to characterize the texture of an image.

The quality parameter is thus derived as the percentage of the frame degraded by these weighted salient packet losses. Figure 5.11 shows an image frame corrupted by packet losses. The temporal difference between this frame, and the previous frame in the sequence is shown in Figure 5.11(b). The hypothesised "salient packet losses" are further weighted by the local entropy (c) to derive the quality statistic (d) for each image frame. The performance of the derived quality metric was evaluated on ground truth MOS scores from the database. The correlation between the derived quality model and human opinion is shown in Table 5.4. The proposed quality model significantly outperforms both the PSNR and SSIM metric, as well as the more recent no-reference video BLIINDS algorithm, for video sequences degraded with packet loss.

Figure 5.11: The proposed Quality model
(a) A frame with two lost packets
(b) The temporal difference between frames
(c) The entropy of the corrupted frame
(d) Salient packet loss



5.7 Summary and Conclusions

In this chapter the influence of packet loss on quality of experience for automotive vision systems has been investigated. A dataset of automotive sequences was created and transmitted through an automotive grade network simulation testbed with varying levels of packet loss. Subjective tests were conducted to obtain ground truth MOS and saliency data. The results indicate that packet losses do not significantly alter the visual attention of the viewer. This is an important result, since it suggests that the visual attention of a driver is more strongly influenced by top-down, task related factors than by sensory cues which are more related to low-level vision.

The results of the subjective test show that although increasing the level of packet loss affects perceptual quality monotonically, it has little effect on viewer attention. The MOS scores further suggest that packet losses in regions of high temporal activity are more salient than those in regions of low temporal activity. A no-reference model for evaluating the quality of video corrupted with packet losses was derived, taking both temporal and spatial masking effects into account. The results demonstrate that the presented model outperforms existing video quality metrics on a dataset of automotive video sequences. The model is generic and shows good correlation with subjective results.

Chapter 6

Conclusions and Future Work

This thesis has presented a number of contributions in the area of next generation in-vehicle networks.

A comprehensive literature review was presented. Current research of physical layer technologies used in automotive networks was presented. Also, application layer technologies such as Audio Video Bridging and Time Trigged Ethernet were explored in depth, including the advantages and limitations of each technology as well as the latest research papers incorporating each system. Publications detailing prototype implementations of Ethernet based automotive networks were also presented. Middleware technology, primarily AUTOSAR, was then discussed and a number of papers highlighed which explore the integration of this widely adopted standard in the automotive domain. Finally, an in depth discussion section identifies emerging trends for the future development of in-vehicle networks as well as challenges and open research questions.

A testbed based automotive simulation network platform has been proposed. The platform was developed using Linux containers to introduce real traffic into the system. The suitability and performance of the platform was rigorously investigated using a number of benchmarking tools at the application, kernel and network level to ensure that the platform could be used for high bandwidth network simulations. These tests showed that the use of a containerised network stack resulted in very small overhead, in all cases below 5% in the worst case.

Multiple candidate automotive network topologies were created, each topology using, where possible, real automotive network flows introduced using the container architecture. All other streams were modelled as accurately as possible on real automotive network characteristics. The scalability of the platform was analysed demonstrating its ability to run in real time for bandwidth values of up to 50.3Mbps using consumer hardware. Simulations were carried out in order to examine the end to end delay and packet delay variation statistics of the tested topologies. Results were obtained for both 100 Mbps backbone networks and 1 Gbps networks. These results were statistically analysed and subsequently compared to those in the literature showing that for common candidate automotive Ethernet network topologies, using standard Ethernet, end to end delay values may be exceeded. This results in a scalable, high performing network simulation testbed for use in the development and test of automotive networks and advanced driver assist applications.

Finally an exploration of the impact of IP network artefacts on image quality where it pertains to automotive networks was presented. A background to objective and subjective image quality measurement was given before an experiment utilising the network simulation platform detailed in Chapter 3 was introduced. This experiment involved the generation of packet loss effected video samples at four different levels of packet loss. The samples used were generated from video captured from a real vehicle fitted with multiple optical cameras. A subjective test methodology based on ITU standards was then outlined. This subjective test included the capture of visual saliency data using a commercial eye tracker in order to identify regions of visual saliency in the samples presented to subjects. From this experiment, which was carried out on 26 non expert subjects, saliency maps were generated which allowed for the exploration of the effects of packet loss on image saliency. Finally, a no reference packet loss image quality metric was presented which outperforms objective image quality metrics such as SSIM and others, with a correlation value of 0.82 compared with 0.42 for Video BLIINDS, allowing for the accurate evaluation of image quality for packet loss effected automotive video.

6.1 Contributions

The main contributions of this work are as follows;

1. The current state of the art of intra-vehicle networking technologies is discussed in a comprehensive review, including physical layer standards, link layer pro-

tocols, and middleware technologies.

2. The development of an automotive Ethernet specific network simulation platform for the evaluation of Ethernet network topologies and configurations is presented.

3. Integration of real world applications into the simulation platform is achieved through the use of lightweight container based virtualisation, allowing direct integration and analysis of different network traffic generating applications.

4. An evaluation of the strengths and weaknesses of the hybrid automotive simulation technique used in this work is given, through the measurement of network stack performance from a kernel, application and maximum bandwidth viewpoint.

5. An automotive specific video quality database of 10 real automotive video samples, each processed at 5 different levels of packet loss is presented. The database is complete with human saliency (eye tracking) data, and subjective MOS.

6. The application of the presented simulation platform in a 26 subject image quality study is presented. An examination of the effects on user attention of network packet loss for automotive environments is explored from the results of the study.

7. The development of a novel saliency based automotive specific no-reference video quality metric which correlates better with MOS than common video quality metrics for packet loss impaired automotive videos

6.2 Future Work

There are a number of potential avenues for future work in this area. Firstly in the area of automotive network simulation, future developments of the presented platform are possible. Improvements that could be added include methods to guarantee bandwidth in multi-camera, very high bandwidth networks. The emergence of link layer protocols such as Ethernet AVB and TTEthernet [84], which aim to provide real time performance guarantees using Ethernet, are promising potential candidates for such networks and are an area of interest for inclusion in the testbed network.

As demonstrated by the experiment carried out in Chapter 5, the testbed provides an excellent platform for use in video related automotive specific experiments. One area of interest is the use of the platform in further image quality experiments, such as those carried out in a realistic vehicle setting to investigate the effects of the automotive environment on viewer attention and visual saliency. Also of interest is the use of the platform in the verification of ADAS under varying network conditions. The effects of network impairments such as packet loss or PDV on ADAS is often not tested and may result in severely degraded performance.

The novel features of this testbed offer potential benefits when applied to an automotive Model Based Development (MBD) workflow as described by Sundharam et al [170][171]. This process is commonly utilised by automotive manufacturers whereby code generation is used to create an application from a high level model. This platform would allow System Designers and Software Developers to test networking and other requirements for ADAS during the design process of an application. This could lead to fewer issues for Software Integrators when the code is tested on functional systems, since at all levels of the design flow the testbed hashelped identify potential issues before they are encountered. Future work would involve investigating ways in which the testbed can be integrated into a MBD process.

A limitation of the approach as presented in this thesis is that applications are required to run on Linux for integration into simulations. Generally modern automotive applications do not use a Linux base and therefore an area of interest for future work is to extend the platform to allow the investigation of platform correctness and the scheduling of application level components. This could be carried out in a number of ways. Firstly, through the integration of ECU devices into the simulation network. This would allow applications to run on a completely resource accurate host. However, these devices aren't readily available outside of automotive manufacturers, so a second option is to modify the platform to constrain resources such that the correctness of automotive algorithms can be tested. This would extend functionality while still allowing the simulator to be run on commodity hardware.

Another potential area of interest would be to explore the verification of the presented platform against a real world prototype in-vehicle network. While the platform has been tested in this work and results compared with those in the literature, this would provide further validation that results obtained from the platform accurately model real world behaviour.

In the area of virtualisation, future work could include the integration of mechanisms to normalise the effects of time dilation in hybrid simulation systems like the one presented. While the effects of time dilation are handled in this work by the capturing of measurements in **Measurement Mode**, it would be useful to mitigate the effects of time dilation in **Real Time Mode** so that the effects can be minimized when extracting video from the platform in real time, i.e. for viewing by a human subject. Such a mechanism for a system based on a similar container based virtualisation platform is explored by Zheng et al [172].

Finally, as shown in Chapter 4, the maximum bandwidth that the testbed is capable of sustaining in Real Time Mode is 50.3 Mbps. In order to fully simulate an automotive network in Real Time for extraction of video from the simulation in real time, this value will need to be increased. This can be done in a number of ways, by increasing the single threaded performance of the simulator using more powerful CPU hardware or by the parallelisation of the simulator so that packet processing takes place across multiple cores. For the style of simulation presented in this work, that is, event driven network simulation which includes traffic from virtualised hosts this is not a straightforward task, as the order in which packets are processed is crucial.

Appendix A

Video Data Capture

In this Appendix, the configuration used for the capture of automotive video data is detailed. The vehicle used for capturing footage was a BMW X5 four wheel drive vehicle with four cameras mounted at various points, front and rear and two side cameras integrated into the vehicles side mirrors. An illustration of the locations of the camera can be seen in Figure A.1

The optical video cameras captured raw uncompressed video at a frame size of 1200 px by 800 px encoded using the lossless Lagarith codec. The cameras are equipped with a fisheye lens and thus the captured video is wide angle. Approximately 4 hours of video footage was captured across a variety of road scenarios, including urban and rural video. Efforts were made to capture a selection of environments including low light and sunny, cloudy and rainy weather.

Samples from videos captured can be seen below in Figure A.2.

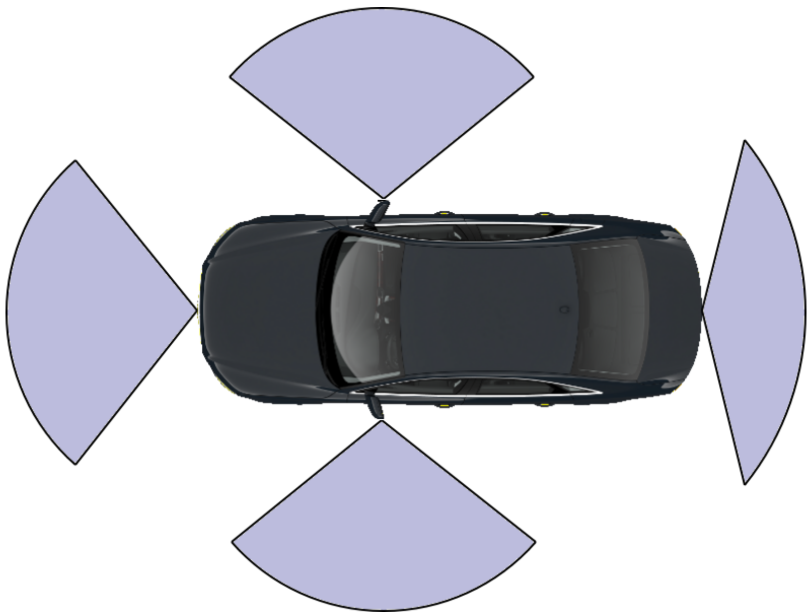


Figure A.1: Locations of cameras used for video capture

Figure A.2: Video Samples from Captured Automotive Footage

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