Heterogeneous Parallel Multi-Radio Transmission System in Wireless Vehicular Communication

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Abstract

In the context of growing demand for mobile data and the emergence of vehicular applications, heterogeneous networks will become a necessity to meet the various requirements of future Intelligent Transport Systems. The aim of this research work is to investigate the use of heterogeneous vehicular wireless networks with multiple independent Radio Access Technologies (RATs). A Multiple Interface Scheduling System (MISS) is proposed, based on a user perspective, where the vehicle has visibility of all the available RATs, with no modification to the fixed infrastructure, operator independent, to improve the performance of vehicular networks. Multi RAT solutions have been reported previously where the packets are scheduled at different layers of the OSI seven-layered architecture but they require modifying the routing protocols, have one IP address per RAT or involve designing specific solution for each RAT. To overcome these limitations, the proposed approach is to schedule the packets at an intermediate layer located between the network layer and the MAC layer. This solution avoids any changes to the RAT standards, and maintains a single IP address.

An adaptive scheduling algorithm has been devised which is comprised of automatic wireless access interface selection, intelligent bandwidth aggregation and allocation, seamless Quality of Service (QoS) support, and context-aware packet scheduling. The system dynamically selects the most suitable wireless technology in a given space and time, or it may use the technologies jointly to maximise the throughput, or improve the reliability that can be achieved with a single radio technology. This work focusses on the uplink, and it addresses the scenario where the vehicle is treated as a data source. The evaluated wireless technologies include cellular (4G) and Wi-Fi (802.11p and 802.11n).

The proposed scheme has been simulated and implemented in hardware to validate the performance of the proposed packet scheduler. The results and hardware implementation demonstrate that the scheduling algorithm is able to transfer packets transparently over multiple RATs to provide higher availability and/or throughput together with prioritization of selected services, without requiring any change to existing wireless standards. In terms of scalability, the intermediate layer approach is shown to be suitable for supporting connectivity by increasing the availability of uplink connection with the current infrastructure. Such an approach is not only valid for heterogeneous vehicular networks but can be used by mobile devices and the future internet of things where the goal is to upload information from different devices anywhere and at any time.

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List of Abbreviations

ABC Always Best Connected

AC Access Category

ACK Acknowledgement

AISF Arbitration Interframe Space

AP Access Point

ARIB Association of Radio Industries and Business

AVHN Advanced Heterogeneous Vehicular Network

BEF Bandwidth Estimation Function

BLE Bluetooth Low Energy

BSM Basic Safety Message

BSS Basic Service Set

BTP Basic Transport Protocol

C-ITS Cooperative Intelligent Transport Systems

CALM Continuous Air interface Long and Medium range

CAM Cooperative Awareness Message

CAV Connected Automated Vehicle

CCH Control Channel

CDF Cumulative Distribution Function

CDMA Code Division Multiple Access

CoA Care-of Address

CoDel Controlled Delay Management Queue

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance

D2D Device-to-Device

DCE Direct Code Execution

DDoS Distributed Denial-of-Service

DENM Decentralized Environmental Notification Message

DES Discrete Event Simulation

DHCP Dynamic Host Configuration Protocol

DIFS Distributed Interframe Space

DSRC Dedicated Short-Range Communication

EDCA Enhanced Distributed Channel Access

EDPF Earliest Deadline Path First

ERP-OFDM Extended Rate Physical OFDM

ETSI European Telecommunications Standards Institute

FIFO First In First Out

FM Frequency Modulation

FPGA Field-Programmable Gate Array

FSPL Free Space Path Loss

GN GeoNetworking

GRA Grey Relational Analysis

HLL Heterogeneous Link Layer

HNN Hopfield Neural Network

ICT Information and Communication Technologies

IEEE Institute of Electrical and Electronics Engineering

IETF Internet Engineering Task Force

IP Internet Protocol

IPv4 Internet Protocol Version 4

IPv6 Internet Protocol Version 6

ITS Intelligent Transport Systems

IPSec Internet Protocol Security

ITU International Telecommunication Union

IVC Inter-Vehicle Communication

HA Home Agents

HAV Highly-Automated Vehicle

HetVNET Heterogeneous Vehicular Network

HLL Heterogeneous Link Layer

HR/DSSS High Rate Direct Sequence Spread Spectrum

HVS Human Visual System

HWN Heterogeneous Wireless Network

LAN Local Area Network

LIFO Last In First Out

LLC Logical Link Control

LTE Long-Term Evolution

MAC Media Access Control

MADM Multiple-Attribute Decision Making

MANET Mobile Ad-Hoc Network

MCDM Multiple Criteria Decision Making
MEW Multiplicative Exponential Weighting
MIH Media Independent Handover
MIMO Multiple Input Multiple Output
MISA Multiple Interface Scheduling Algorithm
MISS Multiple Interface Scheduling System
MRTD Multiple Radio Transmission Diversity
MODM Multiple Objective Decision Making
MOS Mean Opinion Score
MTU Maximum Transmission Unit
MW Multiplicative Weighting
NAIRHA Neighbourhood Aware Vehicular Handover Algorithm
NAT Network Address Translation
NoF Number of Frames
ns-3 Network Simulator 3
OBU-ITS Oxford Brookes University Intelligent Transport Systems
OFDM Orthogonal Frequency Division Multiplexing
OS Operating System
OSI Open Systems Interconnection
PDF Probability Distribution Function
PDR Packet Delivery Ratio
PDU Protocol Data Unit
PoA Point of Access
PQ Priority Queue
PSNR Peak Signal to Noise Ratio
QCI QoS Class Identifier
QI Quality Indicator
QoE Quality of Experience
QoS Quality of Service
RAN Radio Access Network
RAT Radio Access Technology
RGB Red-Green-Blue
RN Relay Node
RR Round Robin
RSS Received Signal Strength
RTOS Real-Time Operating System
RTT Round Trip Time

SAE Society of Automotive Engineers

SAW Simple Additive Weighting

SCH Service Channel

SDN Software Defined Network

SDR Software Defined Radio

SIFS Short Inter-frame Space

SINR Signal to Interference and Noise Ratio

SJF Shortest Job First

SSH Secure Shell

SSL Secure Sockets Layer

STA Station

SUMO Simulator of Urban Mobility

TCP Transmission Control Protocol

TCPW TCP Westwood

TLS Transport Layer Security

TOPSIS Technique for Order Preference by Similarity to an Ideal Solution

TTL Time to Live

UMTS Universal Mobile Telecommunications Service

USDOT United States Department of Traffic

USRP Universal Software Radio Peripheral

VANET Vehicular Ad-Hoc Network

V2V Vehicle-to-Vehicle

V2I Vehicle-to-Infrastructure

V2X Vehicle-to-X

VEINS Vehicles in Network Simulation

VHO Vertical Handover

VLC Visible Light Communication

VN Vehicular Networks

WARP Wireless Open Access Research Platform

WAVE Wireless Access in Vehicular Environment

WCDMA Wideband Code Division Multiple Access

WiMax Worldwide Interoperability for Microwave Access

WLAN Wireless Local Area Network

WSMP WAVE Short Message Protocol

ZOR Zone of Relevance

Chapter 1

Introduction

"People in the 'middle ages' didn't know they were living in the 'middle ages'."

[Benedict Evans]

1.1 Motivation

The main motivation behind this research work is that the availability of multiple independent Radio Access Technologies can be used to improve spectral efficiency and availability. Spectral efficiency, capacity improvements and availability can be achieved by means of user scheduling across multiple Radio Access Technologies (RATs) where users are allocated to RATs with the best channel conditions [1]. To implement a multi RAT solution, an intermediate layer between the Media Access Control (MAC) and Network Layer has been developed, hereby also referred to as the 'Shim Layer'. Cellular technologies, such as 3G/4G-LTE (Long Term Evolution), and Wi-Fi technologies, 802.11p and 802.11n (2.4 GHz and 5 GHz) have been considered as RAT technologies to evaluate the Multiple Interface Scheduling System (MISS), hosted in the shim layer. The system can dynamically select the most suitable wireless technology in a given space and time or may use the technologies jointly to maximise the throughput or improve the reliability that can be achieved with a single radio technology. The selected approach will depend on the traffic profile, i.e. priority (data type packets) or quantity of information to be sent/received.

There are at least two scenarios for which the heterogeneous system and scheduling algorithm could be used. The first category is user devices, such as mobile phones and laptops, that have the capability for dual connectivity over multiple wireless technologies. In this case, the host could efficiently use both interfaces simultaneously or use a primary interface, with automatic redirection of all packets over another interface upon failure of the primary one. The second category is vehicular networks, which have more demanding requirements because the source might be moving, wireless availability might change rapidly and safety messages need to be prioritized. This characteristic prompts the development of opportunistic higher layers that should take advantage of a good link while it lasts without counting on its longevity. The shim layer was designed with the latter form of concept in mind but also supports the former.

The following sections will address wireless communications in Intelligent Transport Systems (ITS), heterogeneity, and vehicular networks. The term 'heterogeneous' is first defined in Section 1.2 followed by a discussion about Wireless Communications in ITS (Section 1.3) which treats about the key features of vehicular communication. The objectives and challenges of this thesis follow in Sections 1.4 and 1.5 respectively, and the novelties and contributions are presented in Section 1.6. Finally, the thesis structure in Section 1.7 concludes this chapter.

1.2 What is Heterogeneous?

The rapid growth in wireless technology in recent years means that there is wide coverage of wireless networks. New technologies have been deployed with coverage overlapping one another, hence forming a hybrid network for wireless access, which is usually called heterogeneous wireless networks [2]. Heterogeneous refers to a technology that is different, or diverse, from its surrounding technologies.

A multi RAT heterogeneous terminal features interfaces for multiple technologies. Integrated architectures are expected not to require modifications at the lower layers so that different wireless technologies can operate independently [3]. A user can be connected to another user via a variety of independent access technologies as depicted in Figure 1.1. To cope with the introduction of heterogeneity into data access, it is critical to identify and devise strategies that can cater to various user profiles and can maximize system performance and more importantly, improve users' quality experience [4]. The goal is to have a heterogeneous architecture and services that together provide seamless integration of single-hop networks and multi-hop wireless systems. The resulting two scenarios are thus considered: 1) single-hop: the packets are sent to the same receiving host, although they follow different network access paths, through different base stations/access points; 2) multi-hop: users communicate directly in an Ad-Hoc mode. In the first scenario, the complexity of the interchange between technologies can be done on the backbone of the system and this is currently the case: the Internet can be accessed through different RATs and from different devices. In the latter scenario, one of the challenges is to produce a scheduling algorithm that is able to react correctly if two communicating devices have different profiles. For example one device that has only a long range cellular link available and the other with a profile which prioritizes the use of short range technologies.

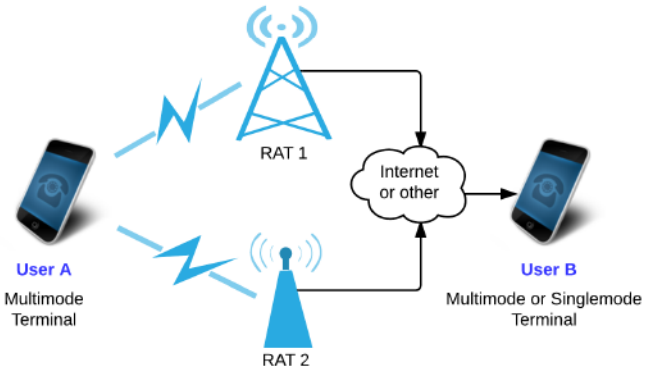


Figure 1.1: Multimode terminal connection

The design of heterogeneous networks should be on the basis of intelligent integration of readily available technologies in order to minimize the deployment cost and to make the deployment fast. However, the design should also be left open to any better substituting or complementing alternatives [5]. The novel shim layer introduced in this thesis aims to respond to all these requirements.

1.3 Wireless Communications in Vehicular Network and ITS

One of the goals of heterogeneous wireless communications for vehicles is to extend the available information horizon beyond traditional sensor systems (radar, cameras), which are all line of sight technologies. Vehicles and infrastructure would cooperate to perceive potential dangerous situations in an extended space and time horizon.

Vehicles are already sophisticated computing systems, with several computers and sensors on board, and will become more and more sophisticated in order to gather information not only from the operational state but also from their general environment. The vehicles are aimed to be connected 'any place and any time'. According to the ETSI 102 638 technical report [6], 20% of the running vehicles will have communication capabilities in 2017 and by 2027 almost 100% will be equipped.

Three unique features define vehicular networks: high mobility, large scale and variable density. They have rapidly evolved from their roots as an application of mobile ad-hoc networks and sporadic content provisioning to today's fusion of interdisciplinary research on computer communications. The main concern is finding low-latency, reliable, and efficient methods for disseminating safety data among neighbouring vehicles. Directly applying the existing communication approaches designed for traditional mobile ad-hoc networks (MANET) to large-scale vehicular ad hoc networks (VANET) with fast-moving vehicles can be ineffective and inefficient. VANET is a specific MANET with faster moving nodes, a movement pattern which is limited along the road with fixed directions and a scale which is much larger than MANETs [7]. In addition, applications in VANET are different from MANET as most VANET applications require data to be transmitted to a certain area instead of being transferred to a certain node: multicasting to a certain geographical area is also known as ZOR (Zone of Relevance) [8].

To respond to these challenges, two main categories of vehicular communications can be distinguished: V2V and V2I. Vehicle-to-Vehicle (V2V) connections allow for safety applications such as crash prevention, while Vehicle-to-Infrastructure (V2I) connections enable infotainment and traffic management which can lead to environmental benefits. A term comprising of all vehicular communications is vehicle-to-everything or Vehicle-to-X (V2X). An example of V2X other than V2I or V2V is a communication involving directly a vehicle and a pedestrian (Vehicle-to-Pedestrian): the vehicle can receive messages from a pedestrian's handheld device to alert them of their presence.

Various techniques have been used over time to provide information about traffic and hazardous situations to users: messages are broadcast via the FM (Frequency Modulation) radio temporarily interrupting the user-tuned reception or message signs placed at strategic points (tunnels, bridges, highway connections, bus stops, city entrance). Wireless communications can provide real-time traffic information, suggest alternative routes, and help to reduce congestion. These new services are all based on the real-time acquisition of traffic information directly from handheld devices or vehicles, which act as sensors that travel on the roads [9]. Some of the proposed solutions include the possibility to enable communications directly between vehicles or through a telecommunication infrastructure, such as cellular.

Cellular technologies are presently the only solution to upload data from vehicles to control centres, with a large impact on cellular resource usage [9]. Although mobile cellular networks are capable of providing wide coverage for vehicular users, the delay requirements of real time safety applications cannot always be guaranteed by cellular networks. To answer to the safety needs, Dedicated Short-Range Communication (DSRC) - based on Wi-Fi 802.11p, further described in Chapter 2 and Chapter 3 -, is the envisioned technology to support V2V due to the high availability and very low latency characteristics. Even if DSRC is primarily foreseen for safety purposes, other applications could take benefit from its deployment, such as offloading cellular networks or enabling numerous large scale crowd sensing applications [10].

A potential solution for meeting the broad communication requirements of ITS is the integration of cellular networks with DSRC, forming Heterogeneous Wireless Network (HWN) or the Heterogeneous Vehicular NETwork (HetVNET) [11]. Such an integrated heterogeneous environment enables a vehicle to access a particular network depending on applications needs and types of radio access networks (RAN) available.

This leads to new radio resource management concepts based on user-centric cell-less network paradigms [12]. Effectively managing resource allocation in such a complex environment warrants a fundamental shift from traditional centralized mechanisms toward self-organizing and self-optimizing approaches. These networks can increase the available bandwidth, improve the reliability and resilience of the communication path [13], and improve connectivity by combining the coverage areas of individual RATs [14]. The need for this shift is motivated by practical factors such as the increasing density of wireless networks and the need for communications with low latency [15].

1.4 Objectives

The objective of this thesis is to devise a decentralized, user-centric, traffic-oriented multi-radio, multi-technology, multi-system vehicular scheduling algorithm that is integrated, transparent, and self-configurable to respond to different objectives with radio access technologies under different operators without modification of the existing wireless standards. The complexity of such an environment not only needs to be hidden from the end users, but also needs to be made transparent to the applications [16].

An ITS test bed, (OBU-ITS) later described in Chapter 6, has been developed to provide a platform for experimental evaluation of the proposed heterogeneous wireless communications scheduling algorithm. The aim was to add a robust and reliable wireless communication link to the vehicle. This link could be used to send control commands to the quad bike, or stream video information back to its controller, or to have a remote processing of the images collected by the cameras. The objective is to demonstrate that heterogeneous networks can improve the performance of the communication in a vehicular network.

1.5 Challenges

The challenges of devising such a scheduling algorithm are to maintain the quality (error rate and latency) and availability of the communication link in the highly dynamic nature of vehicular networks. Another challenge is the complexity of integrating multiple independent RATs, which have no coordination between them. Other important issues include co-channel interference, topology discovery, route creation, mobility, handoff management, and load balancing.

In addition, the scheduling algorithm needs to respond to demanding heterogeneous users, each of which has its own type, objective and information. No changes are to be made to the existing wireless standards, the networks do not have to be under the same operator and thus the implementation costs of this solution are low. More detail about the technical challenges is given in Chapters 2 and 3.

1.6 Novelty and Publications

Multi RAT solutions have been reported previously where the packets are scheduled at the network layer [17, 18], but this requires modifying the routing protocols. Other solutions have scheduled the packets at the transport layer [19, 20] but this additionally requires two IP addresses and requires twice the number of acknowledgements. Solutions with packet scheduling at the MAC layer have also been reported [21, 22] but this requires a specific solution for each RAT to comply with the respective RAT standard. To overcome these limitations the proposed approach is to schedule the packets at an intermediate layer located between the network layer and the MAC layer. Such an approach with the specific combination of RATs is novel for vehicular wireless networks. The proposed solution requires a deviation from the OSI (Open Systems Interconnection) seven-layered architecture, but avoids any changes to the RAT standards and maintains a single IP address.

The devised adaptive scheduling algorithm is comprised of: 1) automatic wireless access interface selection; 2) intelligent bandwidth aggregation and allocation; 3) seamless Quality of Service (QoS) support; 4) context-aware packet scheduling. The system dynamically selects the most suitable wireless technology in a given space and time, or it may use the technologies jointly to maximise the throughput or improve the reliability that can be achieved with a single radio technology. The scheduling algorithm can allocate priorities for different traffic types, with safety critical applications receiving the highest priority.

The opportunities related to the deployment of IP based cellular infrastructures, LTE and WiMax, leads to the possibility of heterogeneous networks with an exclusively IP structure. To this end, as previously mentioned, the considered technologies are cellular, such as 3G/4G-LTE (Long Term Evolution), and Wi-Fi technologies, 802.11p and 802.11n (in both 2.4 GHz and 5 GHz bands). Only some works have considered three or more technologies [23]. Except 802.11p, the technologies observe a common characteristic of one-hop (single-hop or infrastructure) operation mode, wherein users access the system through a fixed Base Station (BS) or Access Point (AP) connected to a wired infrastructure.

In addition to the simulation results a hardware test bed was established to carry out practical measurements and show the feasibility of such a system in a real-world environment.

The results from this work have been published in the following conferences and journal papers:

Conference papers:

- C. Roman, P. Ball, and S. Ou, "A shim layer for heterogeneous wireless communications scheduling in intelligent transport systems," in *2015 IEEE Symposium on Computers and Communication (ISCC)*, pp. 174–179, July

2015

- C. Roman, P. Ball, and S. Ou, "Performance evaluation of dynamic scheduler in multiple queue shim layer for heterogeneous vehicular communications," in *2015 IEEE Globecom Workshops (GC Wkshps)*, pp. 1–6, Dec 2015

- C. Roman, M. Sapienza, P. Ball, S. Ou, F. Cuzzolin, and P. H. Torr, "Heterogeneous wireless system testbed for remote image processing in automated vehicles," *IEEE/IET International Symposium on Communication Systems, Networks and Digital Signal Processing (CSNDSP)*, to be published 2016

Journal papers:

- C. Roman, P. Ball, and S. Ou, "Multiple interface scheduling system for heterogeneous wireless vehicular networks: Description and evaluation," *Special Issue of Software Defined Radio and Network of the EAI Transactions on Wireless Spectrum*, to be published 2016

- C. Roman, R. Liao, P. Ball, and S. Ou, "Mobility and network selection in heterogeneous wireless networks: User approach and implementation," *Network Protocols and Algorithms*, vol. 8, no. 2, pp. 107–122, 2016

This work was also accepted for presentation at the TU Graz International Summer School on Smart Cars (IS3C) in 2015 and at the IEEE ComSoc Summer School 2016 (poster entitled 'User-centric Heterogeneous Wireless Connectivity in Intelligent Transport Systems').

1.7 Thesis structure

The proposed shim layer concept and the multiple interface scheduling system (MISS) have been simulated and critically analysed using discrete event simulation. This thesis also brings experimental verification of the uplink scheduling algorithm via hardware implementation. The thesis is organised in 7 chapters:

- Chapter 1 presents the background on the motivation for this thesis and the ideas behind heterogeneous wireless systems.

- Chapter 2 discusses the literature in terms of heterogeneous networks and vehicular wireless networks.

- Chapter 3 presents the architectural challenges of the shim layer and the general overview of its benefit.
- Chapter 4 outlines the mathematical modelling and system model.
- Chapter 5 evaluates the shim layer and simulation results are presented.
- Chapter 6 describes the implementation and presents the hardware/test-bed results.
- Finally, Chapter 7 concludes this thesis and introduces several guidelines for future research.

Chapter 2

Related Work

"The fuzzy variables are fuzzified and converted into fuzzy set by a singleton fuzzifier"

[L. Wang and G. S. G. S. Kuo [2]]

2.1 Introduction

The concept of heterogeneous networks and multi-radio transmission diversity has been studied over the past 15 years but has gained considerable interest in the last few years with the emergence of vehicular technology and 5G cellular networks. In this chapter the related work reported in the literature is described for both vehicular and non-vehicular heterogeneous wireless networks. Section 2.2 discusses the paradigm of heterogeneous wireless networks, the scenarios involved and the selection algorithms. Research approaches where the scheduling occurs at different layers is discussed in Section 2.3. The key network features of Intelligent Transport Systems and message categorisation are then presented in Section 2.4 to understand the context and the requirements to be met. An overview of the RATs used in a variety of projects are discussed in Section 2.5. Finally, examples of hardware implementation of vehicular networks including heterogeneous solutions are presented in Section 2.6.

2.2 Heterogeneous Networks

Presently, technologies are generally seen as alternatives, but in the field of wireless communications it is envisioned that different wireless technologies may be used cooperatively in order to enhance the throughput available to the end user and/or the network efficiency [29]. In the context of growing demand for mobile data and the emergence of vehicular applications, heterogeneous parallel transmissions will become a necessity to meet the growing capacity requirements. Hoon Kim et al [30] argued that networks with multiple radio access technologies will become one of the most prevalent features in next generation mobile networks (5G and possibly beyond). The case of tighter integration among RATs is studied by Karimi et al. [31] where it is shown that the gain of heterogeneous networks, over independent RATs, in terms of throughput and spectral efficiency varies between 15% and 60% [12].

2.2.1 Selection Algorithm

In a heterogeneous environment, different networks might be managed by different service providers, so their competition to attract and get more users becomes an important issue. The complexity in terms of the number of different possible allocations increases rapidly with the number of RATs. Different mathematical theories help with the selection but they have different functionalities, which lead to different objectives for their usage in network selection [2]. *Utility theory* evaluates the utility of the value of each attribute. *Multiple-Attribute Decision Making (MADM)* provides a comprehensive theory for the combination of multiple attributes for a decision. *Fuzzy Logic* theory is especially helpful to adjust the values of dynamic attributes since the information of these attributes could be imprecisely collected. *Game Theory* gives the equilibrium between networks, between users, or between networks and users, which helps to balance benefits among multiple entities. *Bayesian* models use the previously collected data to update the probability of a network status hypothesis. On the contrary, *Markovian* approaches assume that future states depend only on the current state and not on previous events. *Matching Theory* provides mathematically tractable solutions for the combinatorial problem of matching players in two distinct sets, depending on the individual information and preference of each player.

There are thus a lot of options to choose from for heterogeneous networks. One of the most studied approach is *Game Thoery*. However, the game between networks does not provide a network selection scheme for users, but it indirectly guides users to think about their corresponding schemes for network selection under a network competition environment. Thus, the game between users considers the problems in which users selfishly select their believed best network, hence causing network congestion and performance degradation. Another popular approach is matching theory where the main goal is to optimally match resources and users given their individual, often different, objectives and learned information. K. Sundaresan et al [32] present an initial design of an algorithm TRINITY which caters to a heterogeneous set of users spanning multiple profiles simultaneously built onto the reference structure - without modifying the current structure of the existing wireless technologies.

Focus on MADM

Since other parameters must be taken into consideration beside the Relative Signal Strength (RSS), the network selection problem can be looked at from the aspect of multicriteria analysis. Multi Attribute Decision Making (MADM) is a branch of Multiple Criteria Decision Making (MCDM) which also includes multiple objective decision making (MODM).

MADM algorithms have been used in heterogeneous wireless network environments, in order to choose the best RAT, to find acceptable alternatives or to find the best alternative [33]. A direct comparison between these algorithms would require the use of another MADM algorithm. They can be split into two main categories: compensatory and non-compensatory.

Compensatory algorithms combine multiple attributes to find the best alternative, such as Simple Additive Weighting (SAW) [34], Multiplicative Weighting (MW) and the associated Multiplicative Exponential Weigthing (MEW) [35], Gray Relational Analysis (GRA) [36] or Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) [37]. Because of its simplicity, SAW is the most popular method in MADM problems. In each successive round of MW, the weights are updated by multiplying them with factors which depend on the payoff of the associated decision in that round [35]. GRA uses a reference matrix, set subjectively by the user, to compare the matrices obtained for each network. An advantage of the GRA approach compared to the other listed algorithms is that it selects the network offering a QoS closest to that which is being requested by the service, and not the network that has the best QoS but far exceeds the services' QoS requirement.

On the contrary, non compensatory algorithms are used to find acceptable alternatives which satisfy a minimum cutoff criterion [2]. Various joint radio access allocation schemes have also been proposed based on heuristic optimization methods that exploit neural networks [38] and genetic algorithms [39]. To choose the different networks based on scores, Fuzzy MADM is particularly interesting for the case when some attributes are better to be set with fuzziness due to the complex environment in a MADM scheme.

2.2.2 Disadvantage of Heterogeneous Networks

Although heterogeneous networks bring advantages, a number of issues arise further discussed in this section. In addition to the duplicate acknowledgements issue [29], delays related to packet re-ordering at the receiving end are common. In Earliest Deadline Path First (EDPF) [17] the scheduling algorithm artificially throttles transfer rates on faster paths with the aim of receiving packets in order and thus reducing the time needed to re-arrange them. This is not an acceptable solution for safety-critical information as it can cause an increase in delay but also a drop in link utilization and throughput. To solve such priority issues, a QoS approach has been taken by the 802.11e amendment with a traffic type classification mechanism but it is only applicable for wireless LAN applications (802.11) and does not include other RATs, such as cellular or Bluetooth.

Bazzi [29] states that if the packet distribution is controlled in parallel transmissions, then the targeted throughput is reached. By applying Multi Radio Transmission Diversity (MRTD), performance gains have been observed in terms of average packet delay, packet loss and output compared to legacy systems which operate under only one network access [18]. It was shown that, although the use of technology combining allows higher throughput for a single user and helps reduce losses with improved efficiency and throughput without consuming much wireless bandwidth [40], it is maybe a counter-productive strategy in a scenario with multiple users acting selfishly [29] [41]. Bazzi concludes that further studies must be devoted to investigate if other algorithms or other conditions can give an improvement in a greater range of scenarios.

It is to be noted that the main goal of network selection is to always select the best network for serving the given application and not focus on load balancing, which can lead to frequent switching [18] and performance degradation. Taking two networks both with low but totally different traffic loads, the load balancing process will ignore the two networks' low traffic loads but retain only the relative large load difference. The result is an unbalanced traffic load between the two networks, that could compromise the importance of other attributes (e.g. delay, throughput) from the network selection algorithm [2]. Performance may be enhanced by limiting path switching to channel variations large enough to ensure considerable performance gain, instead of switching even for small changes, that may not yield any significant gains. Also, activating multiple network interfaces on a multimode terminal may significantly increase battery energy consumption, thereby shortening the terminal's battery lifetime and risking premature transmission termination.

2.3 Scheduling at different layers - 'Striping' point

Striping, as defined by Traw et al. [42], is a general purpose technique for network resource aggregation. The aggregation can occur at different layers of the OSI layered architecture. The layer at which the aggregation occurs is defined as the 'striping' point. Bandwidth aggregation solutions can be classified based on their ability to adapt to changing traffic and network conditions, as done by Ramaboli et al. [14]. The solutions that configure the traffic allocation ratios and distribution policies to match varying traffic and network characteristics are classified as adaptive, while those that are based on static configurations are called non-adaptive. A summary of some of the heterogeneous bandwidth aggregation solutions, can be found in Figure 2.1. A more comprehensive list can be found in [14] or [43].

In previously reported work, scheduling without modification of the wireless standards has been carried out at the application layer [44], transport layer [29] and network layer [18] of the OSI layered data model.

The advantages of scheduling at the application layer is the greater knowledge of application characteristics. The disadvantage is that it increases the complexity and compromises interoperability with existing applications [14]. At the transport layer, Multipath TCP (MPTCP) [19], a modified version of TCP using sub flows to redirect traffic, has been adopted by the Internet Engineering Task Force (IETF). However, in its current state, MPTCP does not include intelligent interface selection and traffic distribution mechanisms [14]. The performance degradation of TCP is the most important issue in any wireless transport layer as all losses are assumed to be due to congestion even if they might be caused by other factors such as channel errors, delay variations, or handoffs.

Network layer scheduling solutions are some of the most studied in the literature (e.g. MRTD [18]) due to the flexibility of the Internet Protocol: scheduling

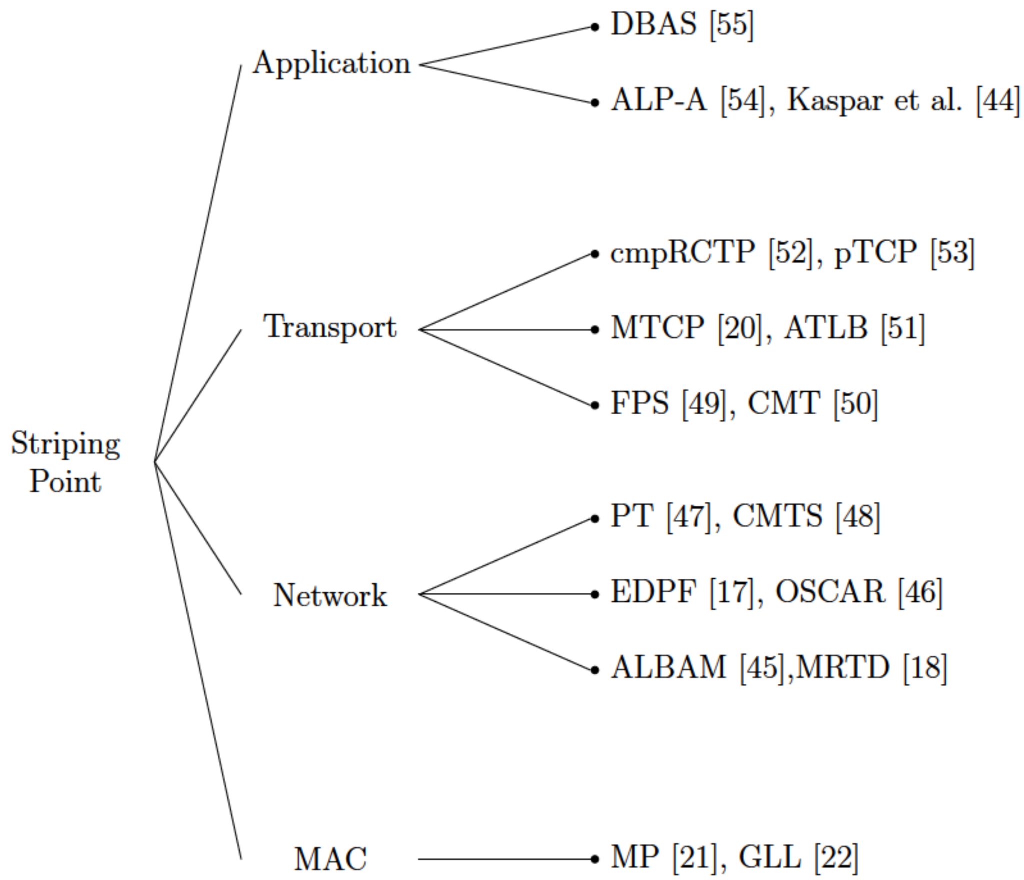


Figure 2.1: Examples of heterogeneous algorithms with striping points at different layers

can be achieved across different domains and infrastructure. Nevertheless, there is poor TCP performance due to high packet reordering [14].

MAC layer solutions can be divided in upper layer and lower layer MAC. The upper layer MAC protocols, although they are very similar to routing protocols (e.g. IEEE 802.11s), use MAC addresses for 'routing', instead of IP addresses. An advantage of scheduling at the MAC layer is that the access selection can operate in response to rapid changes in the radio propagation conditions and which can lead to a higher utilization of the aggregated capacity. A disadvantage is that it requires modification of the wireless standards, which are mainly defined in the PHY and MAC layer specifications.

2.3.1 Scheduling at layer 2.5

The advantage of implementing the data scheduling at an intermediate level between the MAC layer and the IP layer is that the solution is tailored to the available lower layers and transparent to all the upper layers. There would be no modification to the existing wireless standards (physical and MAC layers) and one device can have one IP address (e.g. one IP address is presented to all the RAT interfaces), in contrast to previously mentioned solutions, implemented at the network and transport layers, which require one IP address for each RAT. Another advantage of scheduling between the MAC and the network layer is that the access selection can operate in response to rapid changes in the radio propagation conditions, similar to MAC layer scheduling [22, 56]. A similar intermediate shim layer approach between the network layer and the MAC layer was taken for IEEE 802.21 Media Independent Handoff (MIH), which used a common interface for managing events and control messages exchanged between heterogeneous network devices [57] but was not used for data.

Neighbourhood Aware Vehicular Handover Algorithm (NAIRHA) [58] studies the Vertical Hand Over (VHO) process in Vehicular Networks (VNs) based on the 802.21 standard and takes into consideration the surrounding context, different available types of wireless networks, networking elements information, geolocalisation features, user preferences and application requirements to select the most suitable network. Considering the decision making process, NAIRHA uses the SAW algorithm to evaluate the candidate RAT(s) and choose the most suitable one that meets the multiple requirements defined.

Zheng et al. [59] introduce the Heterogeneous Link Layer (HLL), which operates on top of the MAC layer in each RAN (Radio Access Network) and can also adapt to the underlying radio access techniques. The main objectives of the HLL function are to enable global management of network resources and to meet the QoS requirements of safety/non-safety services by facilitating coordination among various radio networks. The disadvantage with this approach is that it does not follow the TCP/IP layered architecture.

2.4 ITS Network

Before looking into heterogeneous vehicular wireless solutions, a survey of the ITS requirements and services is presented in this section. ITS services, comprised of all modes of transport (e.g. vehicular, rail, air, sea transport), can be broadly categorized into safety and non-safety services [60] - Figure 2.2. The safety related services can be split in four categories, namely 1) vehicle status warning, 2) vehicle type warning, 3) traffic hazard warning and 4) dynamic vehicle warning. An example of user case for each of these categories is respectively:

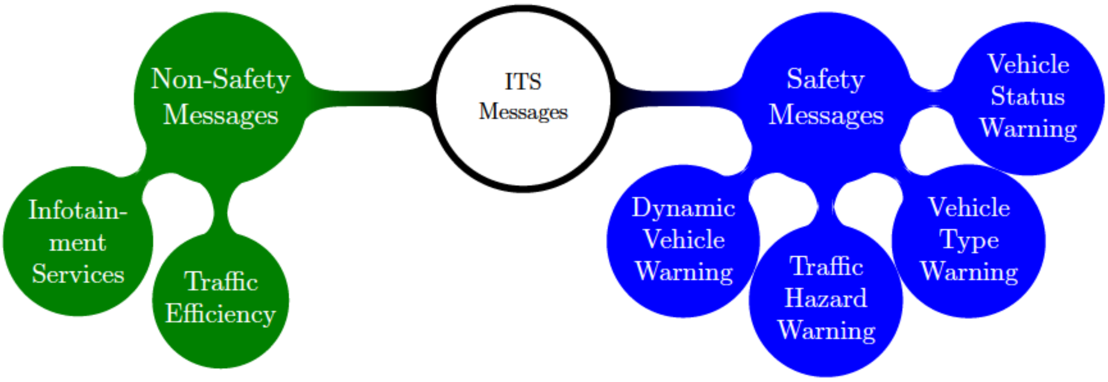


Figure 2.2: ITS Messages Classification

emergency electronic brake lights, motorcycle warning, roadwork warning and overtaking vehicle warning. The minimum frequency of periodic messages of the safety service varies from 1 Hz to 10 Hz, and the reaction time of most drivers ranges from 0.6 to 1.4 s [61]. It is thus reasonable to restrict the maximum latency time to be no more than 100 ms [11].

The non-safety services are used primarily for traffic management, congestion control, improvement of traffic fluidity, infotainment. The main objective of non-safety services is to enable a more efficient and comfortable driving experience. They can be split roughly into two categories: traffic efficiency and infotainment services with applications such as intersection management and media download respectively. Compared to safety services, non-safety services have different QoS requirements. For most non-safety services, the minimum frequency of periodic messages is 1 Hz, while the maximum latency is 500 ms [11].

A non-exhaustive table of the applications can be found in [11] and an illustration of the connected vehicle (C-ITS) application classification, inspired by Picone et al. [62] with data from the European Commision C-ITS platform [63], can be seen in Figure 2.3. In all cases, high-level security is required for both safety and non-safety related services. For instance, in the latter case, monetary transactions such as electronic tolls have to be authorised and endorsed by traffic management authorities. A survey on VANET security challenges and possible cryptographic solutions can be found in [64].

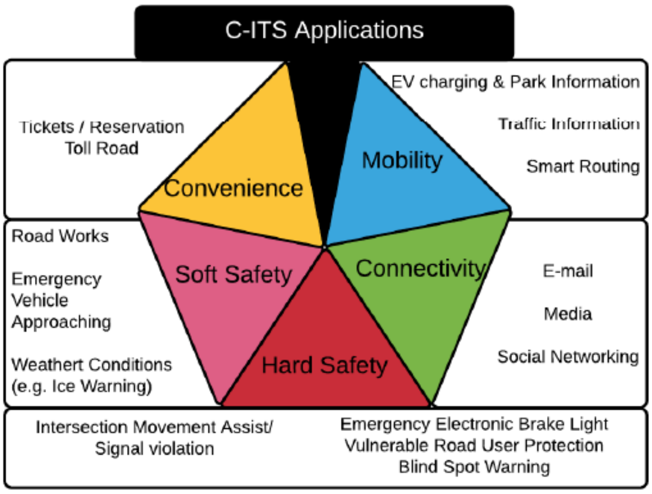


Figure 2.3: Connected Vehicles Applications classification

2.5 RATs for vehicular networks

To support safety-related and non-safety-related messages, the wireless technologies used in V2X communication need to operate in a very dynamic environment with high relative speeds between transmitters and receivers. It is assumed that most vehicles will be able to access the Internet either through the 802.1x access points or through the cellular networks. Vehicle to Vehicle (V2V) or Vehicle to Infrastructure (V2I) wireless communications need to be combined in order to give both short range as well as mid-long range communication options. A solution is needed that can close the gap between long-range cellular technologies, short-range Wi-Fi technologies and the traditional sensor systems which require line-of-sight (e.g. radars, camera). A heterogeneous platform is the best way forward since there is a lack of consensus as to what business model should support this infrastructure [5]. The CALM project [65] addresses long and medium range, while DSRC [65] provides short-range communications between the vehicle and the roadside. These projects are separated and not linked technically. There is therefore an opportunity to interconnect them and focus this work on combining the short-range and the long-range in an unique scheduling algorithm. There is also a need for harmonization and coordination between these different technologies in worldwide ITS initiatives and developments (Japan, Europe, USA) through standardisation bodies such as IEEE, ITU and ETSI. Based on the publicly available information, L. Stranden et al. [66] summarized the scope and applications type of 79 projects that included wireless vehicle-to-infrastructure and vehicle-to-vehicle communications. None of these projects address all types of safety, traffic, and comfort applications, either infrastructure based or ad-hoc to meet the requirements for these applications at the same time.

As automated vehicles have enhanced sensing capabilities through different sensors (radar, infra-red, camera), the range of wireless technologies are likely to interfere. Sturm et al. argue that combining radar and communication systems can allow both environmental sensing and V2X communications to be performed more efficiently [67].

ITS infrastructure is needed to support the above mentioned applications and various services under dense vehicular environments. However, implementing new infrastructures comes at an economic cost and the success rate and sustainability is linked to high penetration rates. The COLOMBO project (Co-operative Self-Organizing System for low Carbon Mobility at low Penetration Rates) [68] tried to overcome this hurdle by asserting the usability from the very beginning of deployment and delivering a set of modern, self-organizing traffic management components being applicable even at penetration rates below 10%.

2.5.1 Cellular technologies

Since the infrastructure of cellular networks has been widely deployed for the past decades, it is economically efficient to utilize cellular networks to support V2I communications [69]. Hossain et al. [5] state that an Advanced Heterogeneous Vehicular Network (AHVN) that uses multiple radios and multiple access technologies in a collaborative manner could be the best candidate for a vehicular network. Their key motivation is that the Dedicated Short Range Communications (DSRC) technology, further described in the next subsection, will only be effective when it is ubiquitously deployed, but this will not happen until the required infrastructure is in place, governments legislate for DSRC deployment in passenger vehicles, and older non-compliant vehicles have retired.

Lequerica et al. [70] have shown that cellular system-aided (3G/LTE) heterogeneous vehicular networks can greatly facilitate message dissemination in terms of message delivery ratio, outperforming pure vehicular ad-hoc networks with sparsely placed vehicles. Based on this research Ho Ting Chen et al. [71] state that one viable option to improve the network connectivity in VANETs for infotainment and road safety service support is via the assistance of a well-established cellular system as a complementary network. However, not all generations of cellular technologies are adequate for use in V2I communications. The 3G system (WCDMA/UMTS) cannot well support safety services in vehicular communications. For instance, the connection setup from an idle state requires

2-2.5 s. The delivery latency is in all the states larger than the allowed maximum latency for safety services (100 ms).

Until 5G is deployed, further described in Section 2.5.6, LTE (4G) is envisioned to support V2I communications especially in the initial deployment stage of vehicular networks and play an important role in rural areas where the vehicle density is low. LTE meets most of the application requirements in terms of reliability, scalability, and mobility support; however, it is challenging to meet the stringent delay requirements in the presence of higher cellular network traffic load [72]. LTE can provide uplink data rates up to 50 Mbps and downlink data rates up to 100 Mbps with a bandwidth of 20 MHz, and supports a maximum mobile speed of 350 km/h. It can service up to 1200 vehicles per cell in rural environments with an uplink delay under 55 ms [60].

The LTE-Advanced (LTE-A) has added a new entity called Relay Node (RN) to enlarge service coverage, providing flexibility of deployment and more flexible IP multimedia services [73]. The available bit rates have increased to 1 Gbps. LTE-A also introduced Device-to-Device (D2D) discovery and communication. LTE D2D communications is a peer to peer link which enables LTE based devices to communicate directly when they are in close proximity. However, the D2D protocol relies on the cellular network assigning the required resources to the user. For example, if two nearby users want to share a file, the network informs the terminals which time-frequency resources can be used for a direct communication. The network initializes the communication and manages the interference generated by the local D2D transmission. This approach does not work for V2V use-cases that have to be fulfilled even when there is no network coverage [74].

Other work has been carried out with technologies such as WiMax (IEEE 802.16e) [75]. WiMAX is a competing standard for wireless broadband internet access. Mobile WiMAX, is used in highly mobile applications, such as handheld devices and in-vehicular internet access. Research has shown, however, that WiMAX suffers overhead problems with high numbers of simultaneous active connections [76].

In general, several problems need to be solved before LTE/WiMax systems can be widely used for V2I communications [77]. As an example, in highly dense areas, such as cities, with numerous building reflections, the performance of cellular connectivity, for both LTE and WiMax, can vary based on the number of users.

Until 5G or a new technology is developed for vehicular networks, and the corresponding infrastructure deployed, the best option is to combine the current available wireless technologies in a multi-radio, multi-technology, multi-system vehicular communications to represent all the opportunities in the plurality in access.

2.5.2 Wi-Fi technologies

One of the complementary networks that could be used to support an integrated approach is the existing Wi-Fi technology with Access Points (APs) distributed around the city [78]. The IEEE 802.11 standard specifies physical (PHY) and Medium Access Control (MAC) layers to set up an infrastructure based wireless local area network (WLAN). Popular standards available on mobile devices (laptops, phones, tablets) include the 802.11 b, g, n and, more recently, higher data rates are reached with 802.11ac. These standards provide good connectivity for nodes that have limited mobility and that do not require extensive handover services. The authentication and association process between a standard device (STA) and an Access Point (AP) reduces the time a node can transmit data within the APs range. Bychkovsky et al. [79] revealed that in urban environments, after a vehicle associates with an AP and acquires an IP address, connection time ranges from 5 to 24 seconds. The Dynamic Host Configuration Protocol (DHCP) requires between 2 to 5 seconds once association is complete, which can take the entire connection time of a vehicle. These standards are thus not fully adequate for vehicular networks. Some concerns are also related to Wi-Fi Protected Access (WPA, WPA2) that provides the security layer of the IEEE 802.11 protocol [62].

Eriksson et al. [80] have introduced QuickWiFi in their Cabernet system, which aims at delivering data to and from moving vehicles using open 802.11 APs. QuickWiFi reduces mean connection time to less than 400 ms from the above mentioned 5-24 seconds interval by creating a client-side process, making Cabernet a viable system for non-interactive applications. Pasavento et al. [81] have used Wi-Fi to create CarFi, which can support current applications seamlessly. Some of the client features are modified, such as the DHCP client which is re-written and optimized for latency. Every time a vehicle successfully connects to an access point, it learns the performance characteristics of that network, and if possible, submits the newly acquired information back to a server. GPS localization estimates the AP performance potential and guides the selection among the available APs. Using GPS information, the mobility prediction can be improved by predicting the path and the next most likely Point of Access

(PoA) within the path [82]. A similar approach was taken by Mendes et al. [83] and Magnano et al. [84] to create a predictive connection manager that is able to choose in advance the best network and technology a vehicle can connect to. The GPS signal is vital in such scenarios and it is important to protect GPS from spoofers [85]. A simpler mode of operation is also available, where the AP decision is solely based on information available locally, such as the Received Signal Strength Indicator (RSSI).

Even though Wi-Fi suffers from high network setup time, 802.11n without any modification can still be useful in congested city areas where car speed does not exceed 15 km/h. Standard Wi-Fi can provide an alternative for non-safety messages and safety messages in the third category previously described in section 2.4 (e.g. traffic hazard warning). This can release the cellular network from extra pressure and reduce cost in the initial stage of deployment. The state of the art progress, as well as future research directions and challenges, for Wi-Fi offloading is surveyed by He et al. [78].

In order to overcome these limitations, the IEEE has realized a new protocol stack WAVE (Wireless Access in Vehicular Environment) which copes with the vehicular requirements: highly dynamic and mobile environment, message transmission in an ad-hoc manner, low latency, and operation in a reserved multi-channel frequency range. The IEEE 1609 standards family defines higher layer services, such as system architecture, security, resource management and communication model, while IEEE 802.11p is focused on physical and MAC layers [62]. The broadcasting of the message via the random access protocol in IEEE 802.11p ensures a fast execution of the transmission at the expense of a less efficient use of the wireless resources.

The de-facto standard for V2X is Dedicated Short Range Communication (DSRC) wireless technology, which is based on the IEEE 802.11p standard, the 1609 Wireless Access in Vehicular Environment (WAVE) standard in the United States of America, the European Telecommunications Standards Institute (ETSI) ITS-G5 standards in Europe, and Association of Radio Industries and Business (ARIB) STD-T75 in Japan. However, in the event of a large number of vehicles, work by Han et al. [86] shows that DSRC in conjunction with IEEE 802.11p exhibits poor performance. Technical detail about the WAVE and ETSI approaches is given in Chapter 3.

2.5.3 Vehicular mmWave technologies

Millimeter-wave (mmWave) devices offer several potential advantages for ad-hoc networks including reduced interference due to directional antennas and building blockages, as well as high bandwidth channels for large data rates. Unlicensed short-range data links can be used in 60 GHz mmWave. The 77 GHz frequency band has also been considered for driver assistance systems based on millimeter-wave radar sensor technology [87]. The mmWave channel is characterized by high path loss and high penetration loss with poor diffraction capability. mmWave with beam switching has the potential of providing multi-Gbps communications in vehicular environments but position prediction accuracy is crucial for the success of the beam switching [88]. Antenna diversity is one of the envisioned solutions to overcome blockage with multibeam antennas, scanning antennas or digital beamforming [89]. Blockage, however, can also help to mitigate interference. Thornburg et al. [90] show that mmWave networks support larger densities, higher area spectral efficiencies, and better rate coverage compared to traditional, lower-frequency ad-hoc networks.

2.5.4 Visible Light Communication

A less conventional RAT has been recently considered for vehicular networks: visible light communications (VLC) or vehicular visible light communication (V^2LC) under the specific vehicular scenario. V^2LC was designed to be used as a complementary technology for the internet of vehicles [91]. VLC would enable short range communication in large, unlicensed, and uncongested bands with limited costs.

The increasing interest in the VLC technology has led to the development of the IEEE 802.15.7 standard. Although it is part of the IEEE 802.15 standard, dedicated to personal area networks, the specifications explicitly consider vehicles and illuminated roadside devices, such as traffic lights or street lights among the addressed applications [91].

The key feature of VLC in relation to other vehicular RATs (DSRC, cellular) is that it operates in unlicensed and uncongested bands. Also, it can use the LEDs available on a vehicle as transmitters and the available infrastructure (street lights) as the access network. The approach can have limited applications for V2V but it could be used to improve the bandwidth available in V2I. Throughput of the order of megabits per second have been already demonstrated for V^2LCs and higher data rates at longer distances are expected for the future [92]. Disadvantages of VLC are its short range, the need for line of sight and high directivity, which can pose issues in broadcasting safety messages. Some safety messages need to be broadcasted omnidirectionally, and if the existing LEDs are used on the vehicle for V^2LC, there are issues related to the side of the car.

2.5.5 Other possible technologies

Bluetooth has been used in V2I for traffic monitoring systems which are capable of identifying vehicles and estimate their travel time in a route [93]. Due to its reduced range and limited bandwidth, Bluetooth (IEEE 802.15.1) is not seen as a technology for V2V but rather for providing users with many convenient features through an in-vehicle wireless network. It is estimated that diagnosis process may become a Bluetooth system level application in vehicles [94].

ZigBee (IEEE 802.15.4) is the key protocol for wireless sensor network applications. Similar to Bluetooth, it offers low data rates but can be used for many embedded applications and intra-car wireless sensor network. One advantage of ZigBee is that it enables uniform mesh networking, which supports the wireless communication between vehicles.

2.5.6 Future technologies

The future 5G (fifth generation) network should be heterogeneous, user-transparent, app-oriented, service-ready, ubiquitous and low cost. The 5G network is expected to have high throughput, low latency (1 ms), large scale sensing (10k sensing), improved resilience, better safety and security, and accommodate different types of devices (fractal heterogeneity). One of the novelties is that the 5G mobile network would exploit the high amount of spectrum in the millimeter wave (mmWave) bands to greatly increase communication capacity [95]. 5G is also expected to make multi-interface, environment-aware, multimode, and multiband communication devices commonplace. The shim layer could respond to such requirements and can be a possible solution for 5G. The adoption of the shim layer in the 5G technology and the use of 5G for vehicular networks with safety related messages depends not only on the technology itself, but also on the policy makers.

A summary table, similar to Jiau et al. [96], depicting the major RATs to be used in ITS systems can be found in Figure 2.1 and an illustration of an

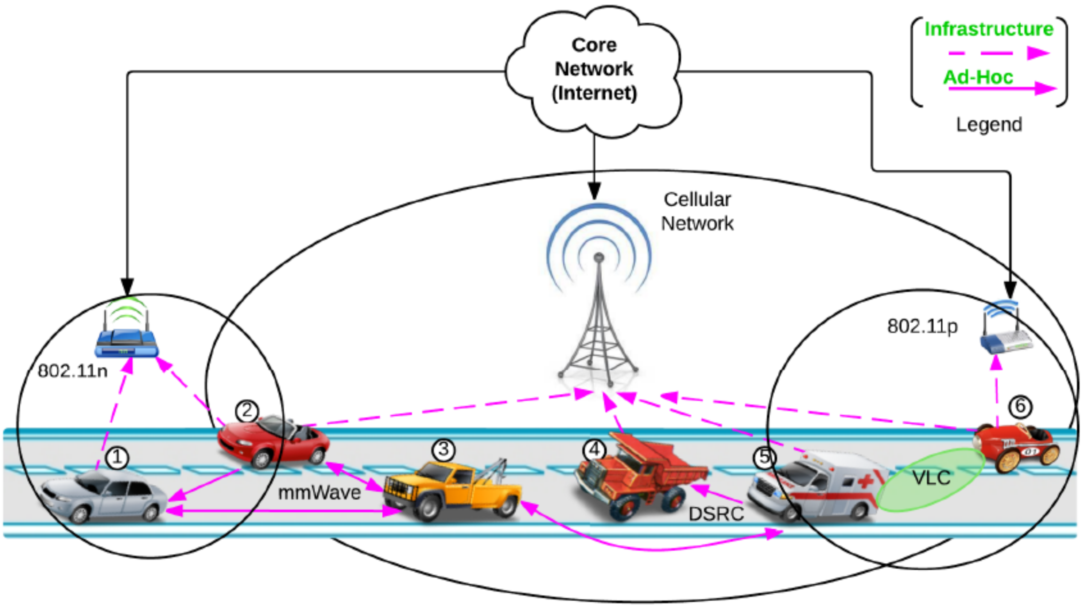


Figure 2.4: Architecture of Vehicular Heterogeneous Network

architecture of heterogeneous vehicular network is shown in Figure 2.4.

2.6 Field Trials and Hardware Implementation

There have been extensive field trials to test the applicability of vehicular network standards in projects such as Safety Pilot[1] in the USA, Drive C2X[2] in Europe, Score@F[3] in France, and simTD[4] in Germany. These field trials reflect the significant investments over the last 10 years to validate the 802.11p technology. Initial investment dates back to 1986 with the Eureka PROMETHEUS[5] and DRIVE I[6] projects in Europe.

A few academic projects have built heterogeneous wireless testbeds that can be used as initial testing for vehicular networking. The WiSHFUL[7] project offers access to several wireless testbeds. Open-Access Research Testbed for Next-Generation Wireless Networks (ORBIT)[8] provides a range of radio resources including: Wi-Fi 802.11a/ac//b/g/n, Bluetooth (BLE), ZigBee, Software De-

[1] `http://www.its.dot.gov/safety_pilot/` - [Accessed:2016-08-02]
[2] `http://www.drive-c2x.eu/project` - [Accessed:2016-08-02]
[3] `https://project.inria.fr/scoref/en/` - [Accessed:2016-08-02]
[4] `http://www.simtd.de/index.dhtml/enEN/index.html` - [Accessed:2016-08-02]
[5] `http://www.eurekanetwork.org/project/id/45` - [Accessed: 2016-09-09]
[6] `http://cordis.europa.eu/telematics/tap_transport/research/16.html` - [Accessed: 2016-09-09]
[7] `http://www.wishful-project.eu/about` - [Accessed: 2016-09-10]
[8] `http://www.orbit-lab.org/` - [Accessed: 2016-09-10]

Table 2.1: Comparison of Wireless Communications for Vehicular Networks

	Short Radio Wi-Fi		Mobile Radio Network				Other Technologies	
	Wi-Fi (WLAN) 802.11a/b/g/n	DSRC/WAVE 802.11p	3G UMTS	WiMAX 802.16	4G LTE	4G LTE-A	VLC 802.15.7	Bluetooth 802.15.1
[redacted]								
Channel Width	10, 20, 40 80, 160 MHz	5, 10, 20 MHz	5 MHz	1.25, 5, 10, 20 MHz	1.4, 3,5, 10, 15, 20 MHz	100 MHz	1 Pixel	1 MHz
[redacted]								
Coverage *Up to*	Small 100 m	Medium 1 km	High 10 km	High 50 km	Very High 30 km	Very High 30 km	Small 10 m	Medium 100 m
[redacted]								
Broadcast	Yes		Yes: Multimedia Broadcast		Yes: Evolved MBMS		Yes	Yes
[redacted]								
V2I	Yes							
[redacted]								

fined Radio (SDR) platforms (e.g. USRP, WARP) as well as LTE and WiMAX base stations and clients. The Carnegie Mellon University (CMU) wireless emulator [97] is a Field Programmable Gate Array (FPGA) based wireless network emulator that allows for the emulation of wireless signals and channels between a series of nodes. HarborNet is a real-world testbed for research and development deployed successfully in the seaport of Leixoes in Portugal [98]. The testbed allows cloudbased code deployment, remote network control and distributed data collection from moving container trucks, cranes, tow boats, patrol vessels, and roadside units.

As commercial products, Connectify Dispatch[9] is a software combining all available network interfaces of a laptop with the use of a proxy server to either increase the bandwidth or load balance the applications. MPTCP with Apple's personal digital assistant (Siri[10]) is an example of heterogeneous network being used for a commercial mobile application. In the past years, a number of companies have specifically developed products for vehicular communications, such as Anritsu[11], Cohda Wireless[12], NXP Semiconductors[13], Veniam (University of Aveiro)[14], Arada Systems[15], YoGoKo (Inria)[16].

[9] `http://www.connectify.me/development/dispatch/` - [Accessed: 2016-09-10]
[10] `https://support.apple.com/en-mn/HT201373` - [Accessed: 2016-09-10]
[11] `https://www.anritsu.com/en-GB/` - [Accessed: 2016-09-10]
[12] `http://www.cohdawireless.com/` - [Accessed: 2016-09-10]
[13] `http://www.nxp.com/` - [Accessed: 2016-09-10]
[14] `https://veniam.com/` - [Accessed: 2016-09-10]
[15] `http://www.aradasystems.com/` - [Accessed: 2016-09-10]
[16] `https://www.yogoko.com/en/main.html` - [Accessed: 2016-09-10]

2.7 Summary

In this chapter the heterogeneous aspects of wireless networks have been reviewed as well as the communication requirements of ITS networks. Combining multiple wireless technologies can be performed at various layers of the OSI stack and the advantages and disadvantages of each solution have been discussed. Different wireless access technology to support ITS have been introduced and assessed. Devising effective and efficient resource management approaches tailored for integrated VANET/3G-LTE hybrid networks is a complex task and needs further investigation. Even though the cellular network cannot be relied on for critical safety applications, LTE (4G) can still handle a large number of ITS applications while UMTS (3G) can only be applied for a limited class of services. Unlicensed data traffic tied to LTE control channels will improve on ease of use, and will be more reliable than Wi-Fi services. The ideal solution is to create a heterogeneous vehicular networking system that leverages the best of both: the ability of 802.11p to support safety-related use-cases, and the ability of LTE-A/5G to support non-safety related use-cases [74].

Chapter 3

The Shim Layer Concept for ITS

"Essentially all models are wrong, but some are useful"

[George E.P. Box]

3.1 Introduction

Each communication standard has unique features at the physical and MAC layers. Above these layers, many communication systems adopt the TCP/IP layered architecture. To implement a flexible heterogeneous network which retains the properties of the data source but can adapt to the selected wireless access technology, a shim layer, located between the network and MAC layers is proposed. The task of the shim layer, is to provide an independent layer over which network, transport and application layer protocols can function efficiently, independent of the access technologies used in each of the point-to-point links in an end-to-end connection. The goal is to meet the Always-Best-Connected (ABC) paradigm [99], applied in heterogeneous vehicular networks. In this chapter, the shim layer is described in detail. The system model is presented in Section 3.2. Assumptions related to the shim layer are presented in Section 3.3, as well as an example of a simple scheduling algorithm. The technicalities and integration details along with a description of the considered RATs (802.11b/g/n, 802.11p, and LTE) are presented in Section 3.4. The DSRC - WAVE and ETSI-ITS 5G vehicular protocols are also described in Section 3.4.

3.2 System Model

To maximise the use of existing standards and to lower the implementation cost, the proposed system maintains the MAC and PHY layers unmodified. A shim layer, referred to as a layer '2.5', is proposed which is inserted between the network layer and the MAC layer of each of the wireless access technologies. Figure 3.1 depicts the system model. The model implementation is based on the IPv6 SixLoWPan module [100], which acts as an intermediate layer between the Network layer and the MAC layer for low power radio systems. The module has been modified to support multiple MAC layers for one node, which allows packets to be sent and received from different technologies.

This shim layer hosts the scheduling algorithm and sends packets to the selected RATs, making the selection transparent for the upper layers. Each RAT exhibits different physical and logical features. They may use different frequencies or modulation schemes at the physical layer, and they may use different media access techniques at the MAC layer. An important feature of this scheme is that one single IP can characterise each node. Such an approach can be implemented for any IP based wireless technology/network and is not only restricted to vehicular networks.

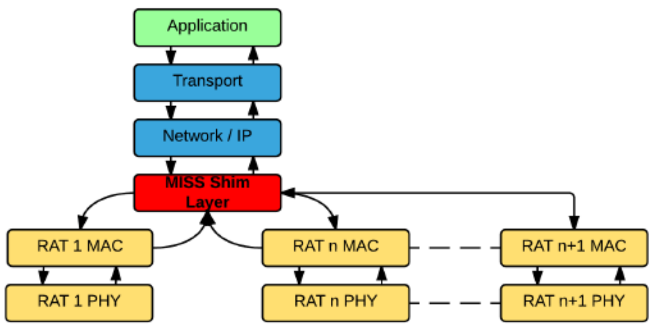


Figure 3.1: Conceptual Model of the Shim Layer

The shim layer consists of a classifier, five traffic category queues and a Multiple Interface Scheduling System (MISS), as shown in Figure 3.2. The 'Classifier' receives packets from the upper layer (IP Layer) and distinguishes between five different packet types: Video, Voice, Background, Best-Effort and

Safety. The first four are similar to the Access Categories (AC) of the Enhanced Distributed Channel Access (EDCA), further described in Section 3.4.3. The 'Safety' packet type is added to accommodate the safety packet transmissions in vehicular networks. The received packets by the 'Classifier' are then placed in different 'Queues' that will be accessed by the 'Scoring System' and the 'Scheduler'. The 'Scheduler' (MISS System) is asynchronous to the classification of the packets in the different queues. The MISS system is divided in two asynchronous parts: the utility scoring system and the scheduler. The scoring system is comprised of a range of utility functions and reference values related to the network performance and the user and service requirements. The scheduler makes use of the scores provided by the scoring system to distribute the packets across different RATs, at each of its iterations: after monitoring the queue sizes, the scheduler requests a score calculation and sends the packets to the appropriate RATs based on the calculated scores, making the process transparent for the upper layers.

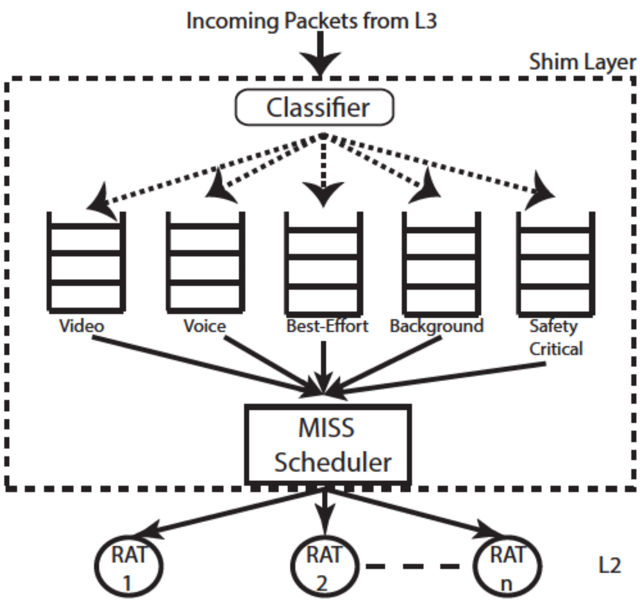


Figure 3.2: Detailed consistency of shim layer

When a packet is received by the underlying MAC Layer, the extracted information is used by the 'Bandwidth Estimation Function' and the 'Reference & Parameters Database'. The 'Reference & Parameters Database' holds the reference values that define the minimum delay and bandwidth necessary for each application/queue type. The entire system (MISS) inside the shim layer and the links between the units is described in detail in Chapter 4.

3.3 L2/L3 shim layer assumptions and considerations

There is an important difference between the uplink and downlink in the shim layer approach. The focus is set on the uplink, rather than the downlink, as several emerging applications treat vehicles as data sources in mobile sensor networks, where a variety of sensors (e.g. GPS, cameras, on-board sensors and diagnostics) acquire and deliver data about the surrounding environment [79]. This information can be used to generate high definition maps, see the behaviour of other vehicles and pedestrians, make more accurate traffic information maps and gather on-street parking space availability.

The uplink model does not require any changes to the current infrastructure as the packets will be forwarded to the Base Station/Access Point and from then on the packets follow a standard route to the destination. The problem of packet reordering at the receiver is handled by the upper layers. A single path is used for downlink. The downlink operator side requires the router in the cloud to have a table specifying the number of interfaces/technologies each user has, check their availability, and redirect the packet to one of the users' points of attachment (BS/AP) to the network. A modification of the network standards on the operator side, or on the receiver side is needed.

Maximum Transmission Unit

It is worth noting that the IP layer will segment UDP packets exceeding the Maximum Transmission Unit (MTU) of underlying layers and will try to reassemble them at the receiving side. The MTU is the size of the largest Protocol Data Unit (PDU) that the device can send. The attribute defaults to 1500 bytes (RFC 894 [101]). If some packets are bigger than the maximum transfer unit (MTU) of the network (1500 bytes for Ethernet, 7981 bytes for Wi-Fi but 2312 bytes for 802.11b), these frames will be segmented into smaller packets to fit the network MTU. This segmentation can introduce extra processing delay.

A larger MTU is more efficient since each network packet carries more user data while protocol overheads (e.g. headers) remain constant. With a large MTU, the same amount of data requires less processing as fewer packets are transmitted. However, the disadvantage is that large packets occupy a slow link for longer periods of time than smaller packets, which can cause greater delays to following packets.

In a shim layer approach the MTU can differ for each technology. Three solutions can arise in this situation: inform the IP layer about the available RATs for a particular package - which would create a cross-layer solution; have a new segmentation of the packets at the shim layer - which would introduce overhead; or use the minimum MTU of the available RATs, reducing the full efficiency of the schemes.

The solution employed for the shim layer is to implement a new segmentation of the packets. The minimum overhead associated with UDP/IPv6 is 52 bytes. With the considered RATs, segmentation is only needed for packets exceeding 1500 bytes as all considered standards have a minimum MTU of 1500 bytes (WAVE and ETSI ITS-G5 have 400 bytes MTU but the underlying 802.11p has a default of 1500 bytes). The percentage of overhead in relation to the packet size is negligible ($52 \div 1500 \approx 3.5\%$) and this solution is the one that is the most advantageous out of the other approaches.

3.3.1 IPv4 and IPv6

IPv6 communications are recognized as a key component to enable traffic efficiency and infotainment applications [102]. The Internet Protocol Version 4 (IPv4) is still widely used today but suffers from several problems. The main problem is the addressing length (32 bits) which is too short to accommodate for growing number of connected devices [103]. Network Address Translation (NAT) has extended the lifetime of IPv4 but IPv6 provides a long term solution, as described below.

For the aggregation solution at the transport layer, some issues need to be solved in relation to the IP connectivity. A TCP connection is identified by a tuple (IP address, port) of both endpoints. The issue is how to maintain a TCP connection when a mobile node changes its IP address as it enters a new access network. One suggested solution is Mobile IP. Mobile IP is designed to allow mobile device users to move from one network to another whilst maintaining a permanent IP address. Each mobile node has two addresses, a permanent home address and a Care-of Address (CoA), which is used when the mobile node is not on its home network [104]. The communication between two nodes is done via Home Agents (HA) that are located in the home networks and which exchange tables about node locations. A node intending to communicate with another node uses its permanent home address as a destination. These packets then get forwarded towards the destination via the foreign home agent using lookup tables.

One assumption of this thesis work is that each vehicle will have a static

IPv6 address and no Dynamic Host Configuration Protocol (DHCP) addressing is necessary to connect to the RATs controlled by operators. With IPv6 a full address auto-configuration mechanism has been defined [105], that allows hosts to configure addresses without any help from a user or DHCP. An IPv6 version of DHCP is useful in cases where there is a desire to centrally manage addresses. In the situation where this is not the adopted route for vehicular addressing, a cross-layer solution such as IP/MAC address masquerading is one option, or Mobile IP.

ITSSv6[1] is a project based on IPv6 for ITS that builds on existing standards from ETSI, ISO and IETF. The IPv6 ITS station stack provided by ITSSv6 supports 802.11p and 2G/3G RATs and is configured differently according to the role played by the ITS station (roadside, vehicle, central).

3.3.2 Security considerations

There are two security aspects that need to be considered in an end-to-end communication system: data and network security. Data security allows the information sent by the user to be encrypted and even if it is intercepted, a key is necessary to decrypt it. The data security mechanism operates at higher layers of the OSI stack and some example protocols at the Application layer are Secure Shell (SSH), Transport Layer Security (TLS) and its predecessor Secure Sockets Layer (SSL). The network security operates at the lower layers and one aspect can be restricting the access to the medium to avoid insertion of unauthorized messages into the network. The given example operates at the Physical layer of the OSI stack but similar mechanisms can be implemented at the MAC layer or IP layer via MAC/IP addresses filtering.

The most widespread data security mechanism is at the IP layer. Internet Protocol Security (IPsec) protects all application traffic over an IP network by authenticating and encrypting every IP packet of a communication session. IPsec supports data authentication, data integrity, data encryption and replay protection. IPsec functionality is similar for IPv4 and IPv6. However, IPsec is embedded within the security architecture of the IPv6 protocol and can utilize the security mechanism along the entire route [106]. Even though IPv6 is a considerable advancement over the IPv4 internet protocol, it does not protect against misconfigured servers, poorly designed applications, or poorly protected websites [107].

[1] https://project.inria.fr/itssv6/

In the shim layer approach, it is assumed that the security and privacy mechanisms are provided by the other layers that have security aspects built in. For instance, apart from IPsec, when connected to a BS/AP, the BS/AP is responsible for the security management through the existing security mechanism (e.g. WPA2 for Wi-Fi) at the MAC Layer. The shim layer with the MISS system only forwards packets to different RATs without modifying the content of the packets. If a packet is encrypted and can not be segmented, the MISS system will send the packet only on the RAT that can accommodate the packet size. Features to mitigate security attacks, such as Distributed Denial-of-Service attack (DDOS) or header manipulation, can still be used with a shim layer approach without influencing the performance of the system.

In conclusion, the same network security mechanisms implemented by individual wireless technologies at the lower layers and data security solutions at the upper layer can still be deployed if a shim layer scheduler is introduced.

3.3.3 Transmission Schemes

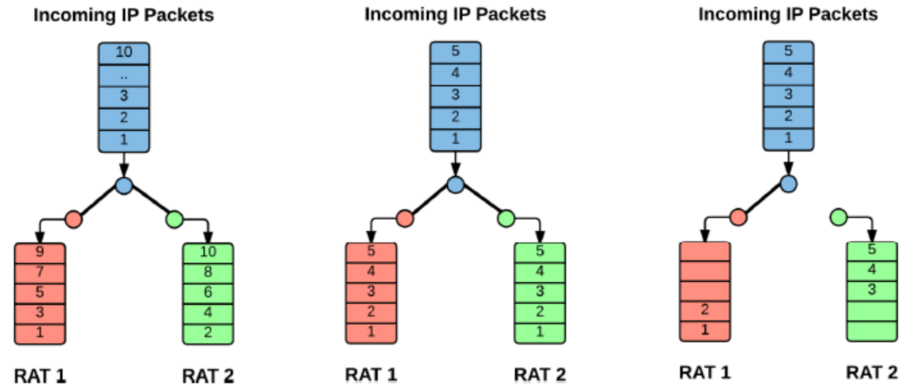
A multi RAT terminal features interfaces for multiple technologies. The packets are sent to the same receiving host, although they follow different network access paths, through different Base Stations/Access Points. Vehicles may use multiple schemes over a short period of time.

Three schemes have been considered for multi radio transmission diversity [18]. The schemes, depicted in Figure 3.3, are defined as follows:

- **Scheme A - Parallel without Redundancy**: packets are sent alternatively on both RAT 1 and RAT 2 - a potential solution for applications requiring high bandwidth, e.g. sending live video streams from a vehicle.
- **Scheme B - Parallel with Redundancy**: same packet is sent on both RAT 1 and RAT 2 - used for redundancy to increase the chances of delivery.
- **Scheme C - Switched Scheme**: only one RAT at a time regardless of the number of packets - cost/energy effective approach.

3.3.4 Example of Simple Scheduling Algorithm

An example of a simple scheduling algorithm implemented in the shim layer based on the three transmission schemes is illustrated in Figure 3.4. For each



(a) Parallel without Redundancy (b) Parallel with Redundancy (c) Switched

Figure 3.3: Different transmission schemes

incoming packet from the upper layer (IP layer), the scoring system outputs a score for each of the RATs with the latest known parameter values. When scheme A is selected, all the networks that have a score higher than 0 will be used for transmission. The packet count (p_t) will decide which RAT will send the packet (line 5 of Figure 3.4). When scheme B is selected, all the networks that have a score higher than 0 will send the same packet. Lastly, when scheme C is selected, the packet will be sent on the RAT that has the maximum score. The packet by packet approach and score calculation responds to rapid changes in the characteristics of the link but does require higher computational power. The MISS system can use any of the transmission schemes at a given time, based on the selected user profile and 'Scoring System' output.

1: **while** packet p_t, $t = 1, ..., m$ **do** $\mathcal{F}_{RATi}, \forall i = 1, ..., n$
2:     **switch** $SEND(\rightarrow)^*$ **do**
3:         **case** *SchemeA*
4:             **if** $\mathcal{F}$ of x RATs > 0 with $x \geq 2$ **then**
5:                 $t \mod x = i, p_t \rightarrow RAT_i$
6:             **else** *Case Scheme3*
7:             **end if**
8:         **case** *SchemeB*
9:             $\forall i : \mathcal{F}_{RATi} > 0, p \rightarrow RATi$
10:        **case** *SchemeC*
11:             $p \rightarrow RAT \max(\mathcal{F}_{RATi})$
12: **end while**

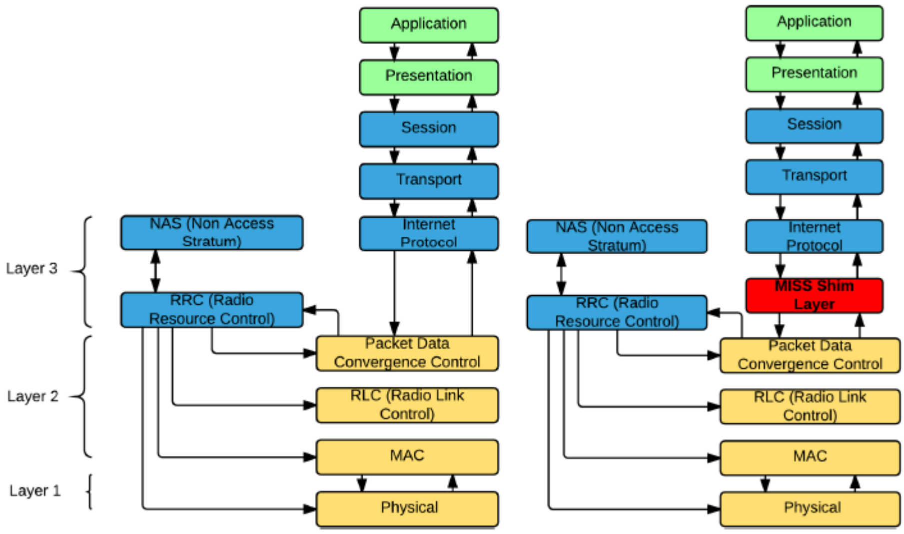
* $\rightarrow$:to be read as *'send on'*

Figure 3.4: Simple Scheduling Algorithm

3.4 Description of considered RATs and integration with the Shim Layer

The shim layer can interface with any IP layer based technology without changes to the standard. The three main RATs considered for this thesis are technically described in this section and how they interact with the shim layer. Network Simulator 3 (ns-3)[2] is the simulator used to implement and evaluate the shim layer. The implementation of the shim layer within ns-3 is illustrated in the following section but the details of the simulator are given in Chapter 5 - MISS Evaluation.

3.4.1 Cellular - LTE

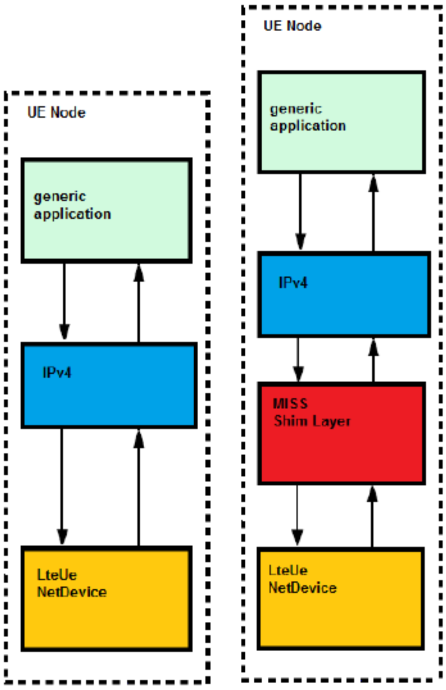


(a) LTE Standard (b) LTE Standard with MISS

Figure 3.5: Illustration of the LTE Protocol Stack

The LTE protocol stack is illustrated in Figure 3.5(a) [108] and the position of the shim layer in Figure 3.6(b). The reason for using another set of queues above the MAC Layer where the queues are usually formed is that in current LTE systems, the MAC layer lacks an efficient scheduling mechanism for proper mapping of vehicular traffic features to the existing QoS Class Identifier (QCI). The ns-3 implementation of LTE and the interactions with the shim layer are presented in Figures 3.6(a) and 3.6(b).

[2]http://www.nsnam.org - [Accessed: 2016-08-17]



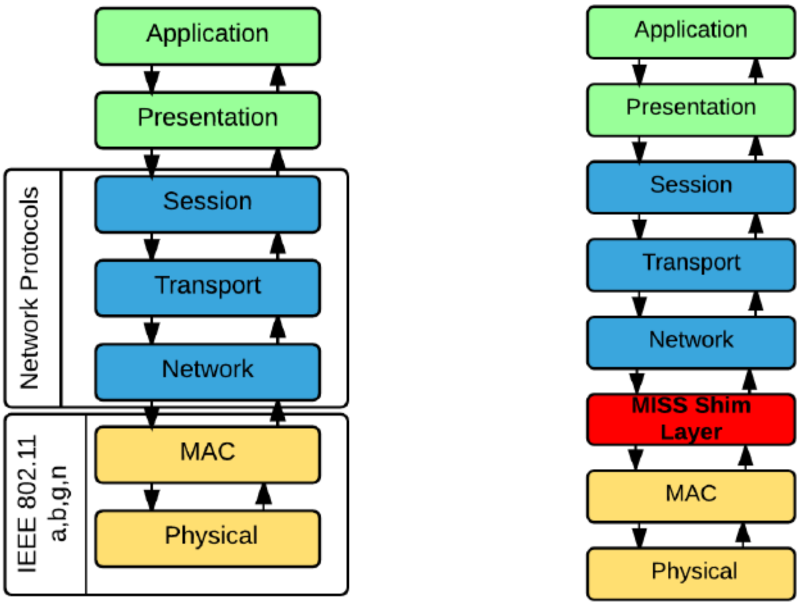
(a) ns-3 LTE (b) ns-3 LTE with MISS

Figure 3.6: Illustration of the LTE Protocol Stack in ns-3

3.4.2 Wi-Fi 802.11 a,b,g,n

The Wi-Fi protocol standard is the simplest compared to the other considered RAT (i.e. LTE) as it defines a set of rules only for the PHY and MAC Layers. The initial standard was released in 1997 and subsequent amendments followed. Even though each new amendment revokes the previous one, each revision tends to become its own standard due to the slow adoption and market penetration rate.

The IEEE 802.11b amendment introduced the High Rate Direct Sequence Spread Spectrum (HR/DSSS) modulation providing a maximum data rate of 11 Mbits/s. The IEEE 802.11a amendment is based on the Orthogonal Frequency Division Multiplexing (OFDM) modulation, which offers a higher data rate - 54 Mbits/s. Differently from 802.11b, this amendment works in the 5.2 - 5.8 GHz frequency bands. The IEEE 802.11g amendment introduces the Extended Rate PHY (ERP-OFDM), which is a transposition of the 802.11a OFDM modulation in the 2.4 GHz band, with minor changes to provide backward compatibility. The IEEE 802.11n amendment defines a high rate Multiple Input Multiple Output (MIMO) modulation format with data rates that can reach 150 Mbits/s. The



(a) Wi-Fi Standard

(b) Wi-Fi Standard with MISS

Figure 3.7: Illustration of the Wi-Fi Standard with and without MISS

book written by Picone et al. [62] is recommended for those wishing to know further details about these amendments.

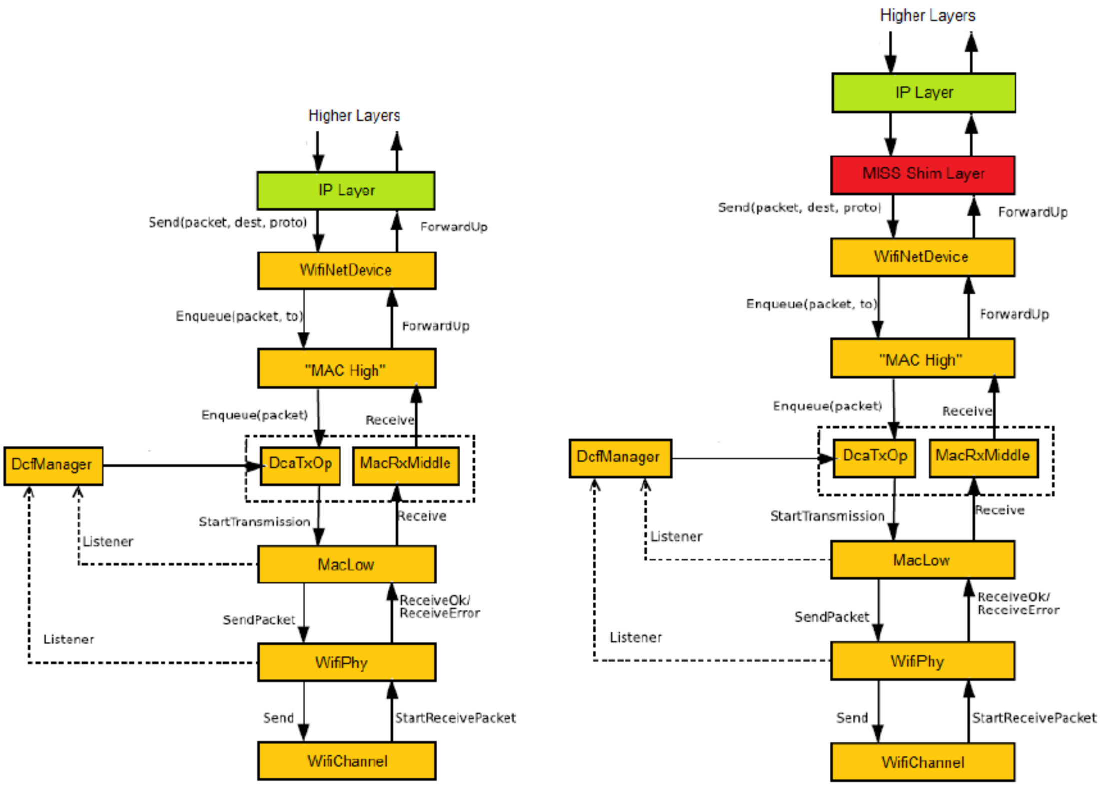
The protocol stack is illustrated in Figure 3.7(a). The MISS shim layer is introduced in Figure 3.7(b). The ns-3 implementation of both standards is depicted in Figure 3.8.

3.4.3 Wi-Fi 802.11p

IEEE 802.11p is focused on the physical and MAC layers and is based on the IEEE 802.11a. Similarly, in ns-3, the 802.11p protocol stack is based on the 802.11a standard[3] and will not be reproduced.

The physical layer is an amended version of the IEEE 802.11a specifications (based on OFDM modulation) with 10 MHz and 5 MHz modes. It also defines new power classes, modified sensitivity and adjacent channel signal rejection requirements. The MAC layer (Figure 3.9) has the same Enhanced Distributed Channel Access (EDCA) core mechanism introduced in the IEEE 802.11e amendment but the communication is outside of the context of a basic service set (BSS).

[3] `https://www.nsnam.org/docs/models/html/wave.html` - [Accessed: 2016-08-05]



(a) Wi-Fi ns-3 (b) Wi-Fi ns-3 with MISS

Figure 3.8: Illustration of the Wi-Fi protocol stack in ns-3

EDCA introduces four Access Categories (AC), each one defining a priority level for channel access and having a corresponding transmission queue at the MAC layer [109]. Each AC in the queue behaves similar to a virtual STA, independently contending with the others to obtain the channel access. CSMA/CA is still used, similar to 802.11a.

The IEEE 1609 standards (WAVE) and ETSI-ITS G5 define higher layer services, such as system architecture, security, resource management and communication model and are based on the IEEE 802.11p. The shim layer can be used with the 802.11p standard but the unified upper layers concept is not fully compatible with WAVE and ETSI ITS-5G without modification of their respective standards. These standards, described in the two subsections below, have specific separate/upper layers (e.g. 'Management' plane in both WAVE and ETSI ITS-G5) in order to support multi-channel operation mode, amongst other features. The shim layer can still be implemented in such systems but it would require specific adjustments to the existing standards on the user side (e.g. modifying the management plane). Examples of the different implementation options are given in the sections below.

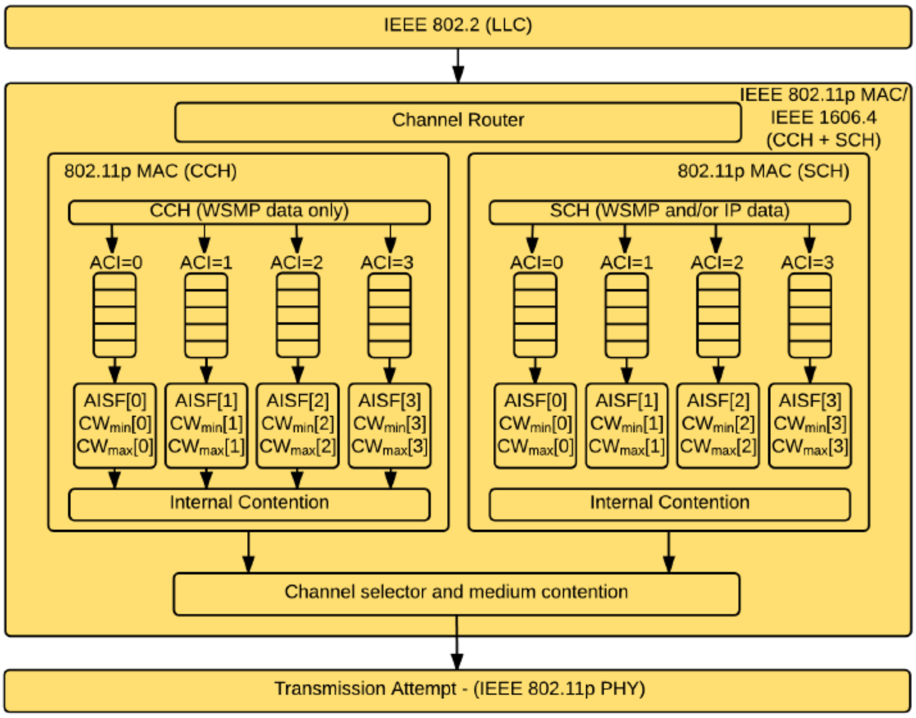
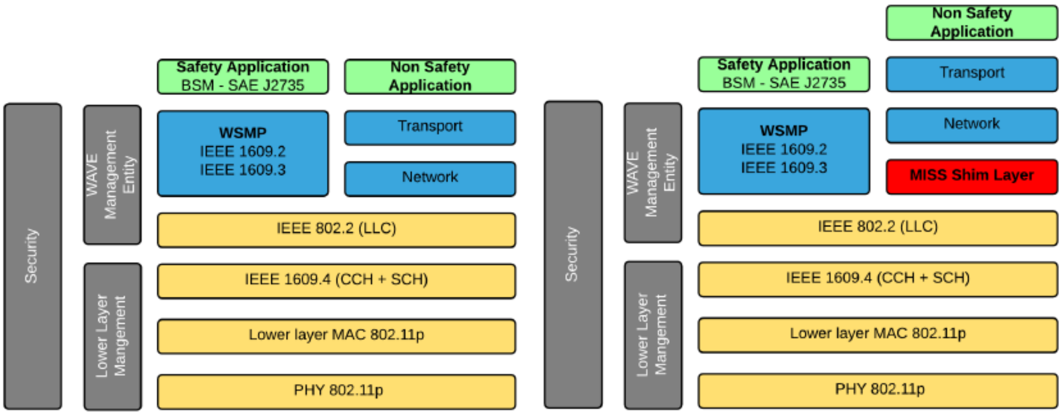


Figure 3.9: EDCA mechanism in the IEEE 802.11p standard

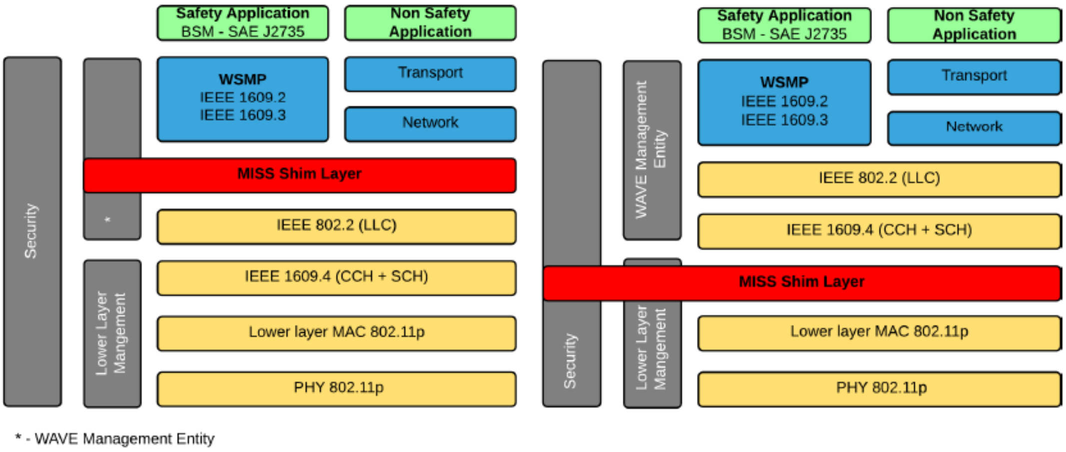
WAVE

In order to meet the requirements of vehicular communications, a suite of standards are defined by the 1609 Working Group for DSRC Networks: 1609.4 for Channel Switching, 1609.3 for network services including the IPv6 based WAVE Short Message Protocol (WSMP), and 1609.2 for security services. To avoid excessive overhead compression, the minimum WSMP overhead is 5 bytes, and even with optional extensions it reaches 11 bytes. This overhead allows applications to directly control lower layer parameters (e.g. 1 byte for security type, 1 byte for channel number). As a comparison the overhead associated with UDP/IPv6 is 52 bytes.

The 'SAE J2735' standard, shown in the WAVE protocol standard [110] illustrated in Figure 3.10(a), specifies a Basic Safety Message (BSM) set, its data frames and data elements specifically for use by applications intended to utilize the 5.9 GHz DSRC for WAVE communications systems. Although the scope of this standard is focused on DSRC, the message set, and its data frames and data elements have been designed, as much as possible, to also be of potential use for applications that may be deployed in conjunction with other wireless



(a) WAVE Protocol Standard (b) WAVE with Shim Layer (Transparent)



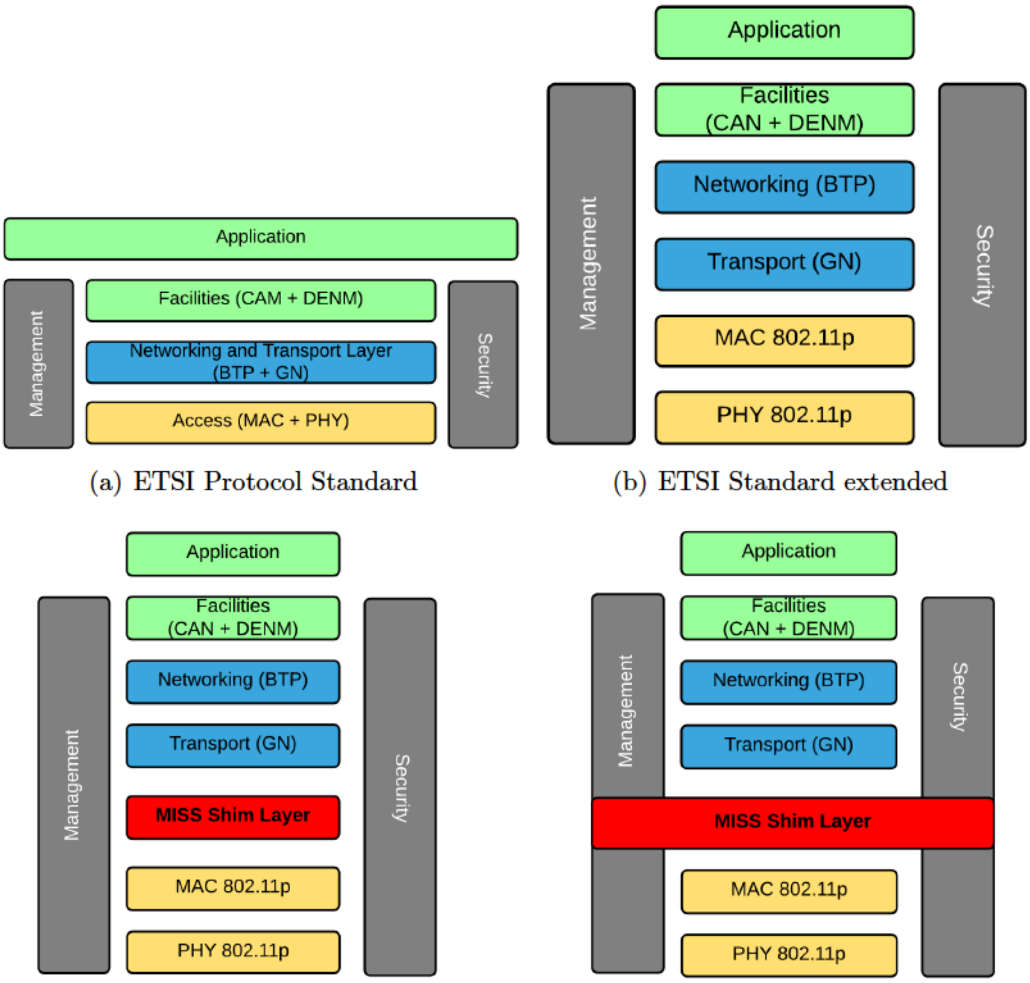
(c) Modified WAVE with Shim Layer - Compromise (d) Modified WAVE with Shim Layer

Figure 3.10: Illustration of the WAVE protocol stack and the shim layer implementation

communications technologies [111]. The standard is currently in its fifth revision.

In ns-3, different from the standard 'WifiNetDevice', the WAVE device will have multiple internal MAC entities rather than a single one. Each MAC entity is used to support a WAVE channel. The shim layer could be introduced to intercept the packets entering the queue and place them in the shim layer queues - Figure 3.10(d). By doing so, the packets could then be sent on a different RAT or the shim layer could be interfaced with different channels of the same technology (802.11p). Such an approach goes beyond the objective of the shim layer since it would then also handle channel selection. A compromise solution is to introduce the shim layer before the packets are sent in the MAC layer - Figure 3.10(c). This would nevertheless still modify the standard (e.g. the channel information given by the WSMP indicated in the overhead will not be used). A transparent implementation of the shim layer is possible for the 'non safety application messages' - Figure 3.10(b).

ETSI ITS-G5



(a) ETSI Protocol Standard

(b) ETSI Standard extended

(c) ETSI with Shim Layer (Transparent)

(d) Modified ETSI with Shim Layer

Figure 3.11: Illustration of the ETSI ITS-G5 protocol stack and the shim layer implementation

The candidate protocol stack for ITS applications in Europe is designed by ETSI and is shown in Figure 3.11(a) - the extended version is also shown in Figure 3.11(b)) [112]. The physical and MAC layers have been standardized in 2009 in the ITS-G5 protocol, which is largely based on IEEE 802.11p. The goal is a 200-800 m communication range. The protocol supports the Basic Transport Protocol (BTP) and the GeoNetworking (GN) protocol. Two types

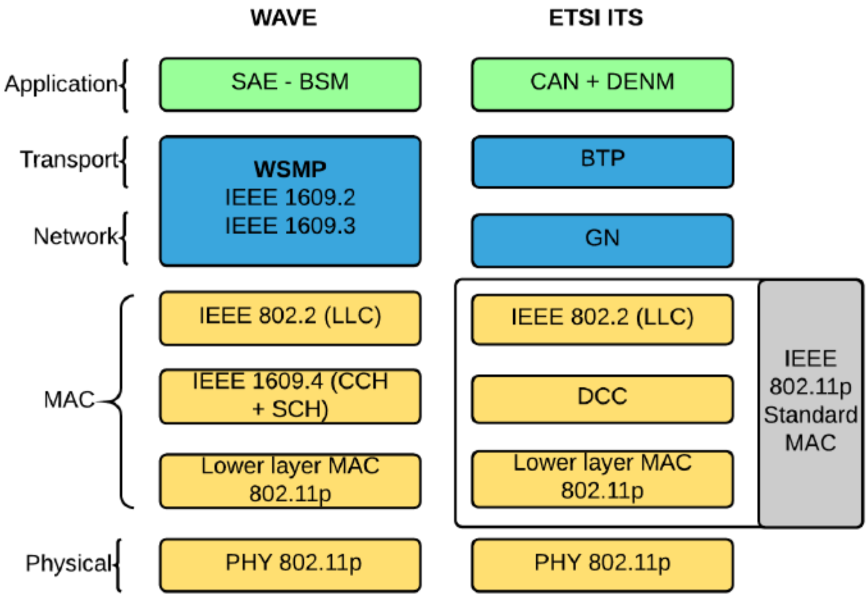


Figure 3.12: Comparison between the WAVE and ETSI ITS-G5 protocol stacks

of safety messages are standardized by ETSI, referred as Cooperative Awareness Messages (CAMs) and Decentralized Environmental Notification Messages (DENMs). CAMs are heartbeat periodic messages, which include speed, heading and position, delivered to vehicles laying in the awareness range of the sender at a frequency of 1-10 Hz. DENMs are event-triggered messages delivered to vehicles lying in the relevant geographical area of the triggering event. Such a region of interest can span several hundred meters.

In Figure 3.11(c) there is a transparent MISS implementation without modification to the standard. In Figure 3.11(d) there is a possible implementation with a modification to the ETSI ITS-G5 standard (non-transparent).

To summarize this section, a comparison between WAVE and ETSI ITS-G5 is depicted in Figure 3.12. WAVE and ETSI ITS-G5 networks can operate well under sparse nomadic deployment with stationary channels, but vehicular communications may take place over severe frequency-selective multipath and fast fading channels, as well as in densely populated environments. Channel congestion, unbalanced link, prioritization and channel selection are some of the issues that need to be resolved for DSRC (WAVE, ETSI ITS-G5) and 802.11p.

3.5 Summary

In this chapter the system model of the shim layer has been introduced and it has been shown how it can interface transparently between different RATs. Different transmission schemes in heterogeneous wireless networks have been discussed and an example of a simple algorithm presented. The advantages of IPv6 over IPv4 for vehicular network were outlined and solutions have been provided for mobile nodes. Devising a system that ensures backward compatibility for legacy technologies such as IPv4 addressing is one of the main challenges that still needs to be addressed. The descriptions of the considered RATs - LTE, 802.11n and 802.11p - for the shim layer, and the implementation in ns-3, revealed how the shim layer can interface transparently with the mentioned technologies. Interfacing with specific vehicular solutions such as IEEE WAVE or ETSI-ITS 5G requires modifications of the standards on the user side if the full features are to be implemented. In all cases, no modifications on the receiver side are needed.

Chapter 4

Multiple Interface Scheduling System (MISS)

"$e = mc^2$: $error = (more\ code)^2$"

[Unknown Author]

4.1 Introduction

The Multiple Interface Scheduling System (MISS) is the core work described in this thesis along with the introduction of the L2/L3 shim layer concept. Section 4.2 introduces all agents of the MISS system model and their interaction. Section 4.3 describes the classification of the incoming packets from the upper layers. The choice of parameters for the scheduling algorithm with the update procedure follows in Section 4.4. Two MADM approaches with scoring systems have been modelled and are presented in Section 4.5. The resulting scheduling algorithm, implemented in the Scheduler, along with the different user policies are discussed in Section 4.6.

4.2 MISS System Model

As previously shown in Figure 3.2, the shim layer consists of a classifier, five traffic category queues and a Multiple Interface Scheduling System (MISS). The MISS system is divided in two asynchronous parts: the utility scoring system and the scheduler. The scoring system is comprised of different utility functions and reference values. The scheduler makes use of the scores provided by the scoring system to distribute the packets across different RATs, simultaneously at each of its iterations. After monitoring the queue sizes, the scheduler requests a score calculation and sends the packets to the appropriate RATs based on the received scores, making the process transparent for the upper layers. All the considered agents are non-preemptive as they can not temporarily interrupt the other shim layer agents.

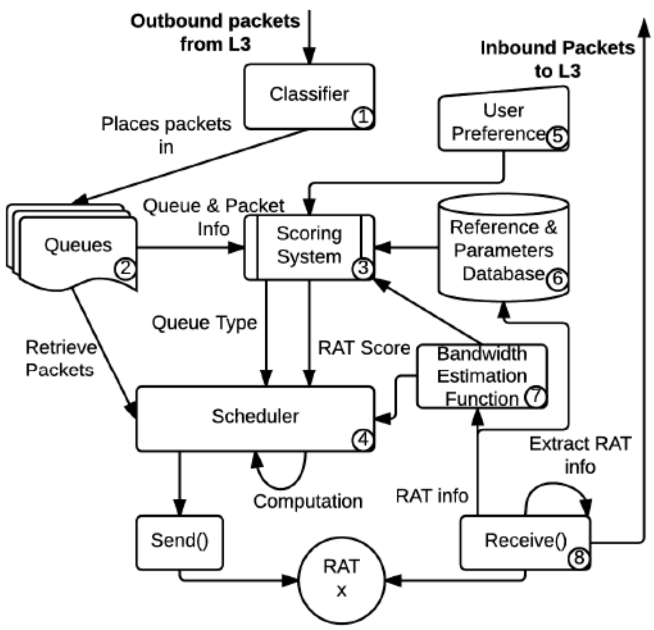


Figure 4.1: MISS System Flowchart

The MISS system model is depicted in the 4.1 and its agents are enumerated and described below:

1. Classifier - Section 4.3.1 describes the classification and the modelling of the incoming packets from Layer 3 (L3).

2. Queues - Section 4.3.2 outlines the queues considered for the system (e.g. FIFO, LIFO, CoDel).

3. Scoring System - based on two MADM techniques (Section 4.5) which take into consideration the User Preference ⑤, Node/Link Parameters ⑥, and Bandwidth Estimation Function ⑦.

4. Scheduler - home of the scheduling algorithm (Section 4.6.1).

5. User Preference - Different policies influence the scoring system and in consequence the distribution of packets at the scheduler (Section 4.6.2).

6. Reference & Parameter Database - stores the reference parameters values (Section 4.4) but also involves the update process (⑧).

7. Bandwidth Estimation Function (BEF) - based on work from Mascolo et al. [113], the BEF is used only when a non packet by packet approach is taken (Section 4.4.2).

8. Receive() - The algorithm relies on path monitoring, such as TCP acknowledgement (ACK) information for updates on bit rate and delay. MAC Layer acknowledgements are an alternative for UDP (Section 4.4.2).

4.3 Handling Incoming Packets from Upper Layer

In this section, the classification of the incoming packets from the upper layer is described and the queue types in which these are placed.

4.3.1 Classifier

Packets arriving from layer 3 (IP layer) are classified into five different queues based on their traffic category (video, voice, best-effort, background and safety critical). The classification of the packets in the queues follows a memoryless property as the past history has no influence on the future. Since exponential is the only continuous distribution with memoryless property, the modelling of the incoming packets from the classifier follows a Poisson distribution:

$$P(x) = \frac{e^{-\lambda}\lambda^{x}}{x!} \tag{4.1}$$

with λ, the average number of events per interval, x, the event values (0,1,2,...), and e, Euler's number. Moreover, it requires that the number of packets arriving in non-overlapping time intervals are probabilistically independent.

4.3.2 Queue Types

All the considered queues are non-preemptive queues as they can not temporarily interrupt the task given by the other shim layer agents. For example, if Round-Robin (RR) queue is used, the queue scheduler could cut the process of sending a packet before it was sent because of the expired allocation time. This could have an impact on the functioning of the shim layer. The RR queuing approach is therefore not being studied.

The First In First Out (FIFO) is a simple queue type but it usually has long/varying waiting time. The Last In First Out (LIFO), also known as a stack, is also a simple queue but it is an unfair approach, especially in saturated environments. Shortest Job First (SJF), inspired from accounting, selects the packet with the lowest size first. One advantage is that it minimizes the queuing delay (different delays explained in Section 4.4.1). However, it has the potential of packet 'starvation' for the packets that require a long time to complete such as large packets. The Priority Queue (PQ) serves the packets with the highest priority first. The Controlled Delay Management (CoDel) queue [114] eliminates the expired packets from the queue, thus reducing the queue time. The CoDel uses the packet-sojourn time through the queue rather than queue size, queue occupancy time or queue-size thresholds. The use of the actual delay experienced by each packet is independent of the link rate, gives superior performance to use of buffer size and is directly related to the user-visible performance [114].

The shim layer proposes a novel approach by combining a priority queue with a CoDel queue approach. The priority queue approach is used to accommodate the safe packets first, and the other types of packets in order of preference. The CoDel queue approach has been chosen in order to de-congest the queues from packets that have time-constrained delivery and for which the time limit can not be met.

4.4 Scheduler Parameters

The parameters influencing the scheduler design most frequently taken into consideration in the literature include bandwidth, delay, jitter, bit error rate, traffic load, security level and packet loss [33]. These parameters are defined from a network operator perspective rather than from a user perspective. When an operator controls all the APs and BSs, they are able to choose the optimal solution for a given user. In addition to the above mentioned parameters, an operator has the availability of other factors which influence the RAT and cell selection:

available services, QoS, cell load conditions, UE interference conditions, user profile, operator preferences and terminal characteristics.

When a user has visibility of multiple APs that are not under the control of the same operator, the optimal selection of access technology should be at the user-end. The users have a different perspective and they may have visibility of multiple APs which are not under the control of a single operator. As discussed in Chapter 2, the selection of a non-optimal network creates undesirable results such as poor customer experience or the use of more expensive network [115].

Six attributes (bandwidth, cost, energy consumption, delay, SINR, and speed of vehicle) are considered for the algorithm and are discussed in the next section. As a comparison, the NAIRHA algorithm [58] parameters include the following: throughput, latency per packet, packet loss ratio and price per MB.

4.4.1 Choice of parameters

The *bandwidth* or instantaneous throughput gives an estimation of the capacity of the RAT.

Delay is a major indicator of QoS and of major importance for delivering safety critical information in ITS. There are four sources of network delay: processing delay, queuing delay, transmission delay and propagation delay. The processing delay is the time between receiving a packet from the upper layers and assigning the packet to an outgoing queue. The queuing delay is the time buffered waiting for transmission. The transmission delay is the time between transmitting the first and the last bit of the packet. Finally, the propagation delay is the time spent on the transmission of the electrical signal and is independent of the traffic carried by the link. The delay mentioned in the MISS scoring system is the latter type of delay - propagation delay. Similar to Multi Radio Transmission Diversity (MRTD) [18], transmitter to receiver packet delay is used as the feedback information mechanism.

The *Signal to Interference and Noise Ratio (SINR)* is used for an effective access selection by tagging the received packets at the underlying physical layer before they are sent to the upper layer. The SINR is useful since it gives a reliable measure of system performance in both noise and interference limited scenarios. This ensures that the user knows exactly what they are experiencing and has the option to change to a better RAT if it is available.

The *cost* and *energy consumption* share the same linear utility model. The cost is a relative monetary measurement of using the network. The same linear concept is applied to energy assessments: the more energy intensive a RAT is, the lower the score. Non real-time applications can use the weights associated to these parameters to optimise the use of their resources.

Mobility is an important factor in ITS. As such, the *speed* of the vehicle influences the estimated availability of the network. The algorithm predicts the network's availability based on the user's speed to prevent the user from connecting to networks that will be out of range before transmitting. This mainly applies to short range technologies such as 802.11x (except 802.11p), Bluetooth and Zigbee. Even though the vehicles are able to successfully associate with APs and also transfer data with a uniform probability at all speeds between 0 and 60 km/h the minimum time before any data is successfully transmitted in vehicular connections to open Wi-Fi is about 5 seconds [79]. If an Access Point has a range of 100 m, a car travelling higher than 70 km/h will not have any successful transmissions. Likewise, the faster the user's speed, the lower the bit rate the user can achieve as it mainly depends on the APs signal strength [116].

An example with empirical values of the described attributes and weights, partly used for one of the performance evaluation simulations later described in Chapter 5, is shown in Table 4.1.

Table 4.1: Selected Attributes and Weights

	Bandwidth (Mbps)	Cost -	Energy -	Speed (m/s)	Delay (ms)	SINR (dB)
RAT 1	54	5	50	5	10	16
RAT 2	54	5	50	5	20	8
Weight	0.1	0.1	0.1	0.1	0.4	0.2

4.4.2 Updating the parameters values

Link reliability can be determined by measuring some physical layer parameters of the subsystem, such as received signal strength and continuous link uptime [117]. These values can be retrieved without modifying any of the current standards and are thus used. The algorithm relies on path monitoring, such as TCP acknowledgement (ACK) information for updates on throughput and delay, when this information is available. Also, standard Wi-Fi MAC client acknowledgements are monitored to determine the signal strength, throughput and packet error rate of a selected path. This is to adapt allocation ratios and transmission schedules to network changes. The delay, bandwidth, SINR and speed are calculated independently from the scheduling algorithm. Every time a new packet is received by the shim layer from the lower layer, their values are updated in a Table, similar to Table 4.1.

Regarding the available bandwidth two sources have been considered, although none of these approaches have yet been implemented in the algorithm: Cabernet approach [80] and/or TCP Westwood [113].

Cabernet System

A simple rate increase rule has been used by Eriksson et al. [80] to implement rate adjustment. The sender considers increasing the rate each time it receives an ACK. This increase rule is similar to the additive increase used in the Transmission Control Protocol (TCP).

$$rate \rightarrow rate + \frac{ack.interval}{(RTT)^2} \tag{4.2}$$

The Round Trip Time (RTT) is squared since the rate adjustment is from the sender to the receiver, while the RTT also includes the return path, from receiver to sender. If the previous packet got no response, the new rate is computed as:

$$rate \rightarrow max(rate(1 - c \cdot p_{loss}), r_{min}) \tag{4.3}$$

with p_{loss}, an exponentially weighted moving average of the loss probability computed from the ACKs, c, a tunable constant empirically determined as $c = 2$, and r_{min}, the minimum rate.

TCP Westwood

TCP Westwood (TCPW) [113] is a modification of the TCP congestion window algorithm of the standard TCP (TCP Reno) to improve performance by continuously measuring the rate of returning ACKs and estimating the available bandwidth.

When an ACK is received at the source at time t_k, it implies that a corresponding amount of data d_k, has been received at the receiver. A sample of the bandwidth used by that connection can be measured by the following:

$$b_k = \frac{d_k}{t_k - t_{k-1}} \tag{4.4}$$

where t_{k-1} is the time the previous ACK was received. Several time filters are applied to average sample measurements. The full details can be found in Section 2.2 of Mascolo et al. [113].

An advantage of this approach is that an ns-3 implementation has been performed by Gangadhar et al. [118] and the work could be integrated in the MISS algorithm. Even though this implementation is at the Transport Layer (L4), the same approach can be used by the MISS system in the shim layer transparently as it a technique that only involves intercepting the packets and performing calculations.

TCP vs. UDP

The transport layer is typically responsible with providing end-to-end services – reliability, flow control, and congestion control. The choice between TCP and UDP in vehicular networks will also determine if these bandwidth estimation approaches will work. UDP is to be mainly used for safety applications due to the delay associated with retransmissions in TCP. If UDP is used, no ACK will be received and the described bandwidth estimation techniques cannot be used but MAC Layer ACK could be monitored.

TCP can be used for non-interactive applications, where bandwidth is of more importance. Another option is to send dummy TCP packets as a heartbeat of the link. This option involves a cross layer mechanism as the shim layer would have to instruct the TCP layer to send dummy packets. However, heartbeat techniques are not uncommon in Operating Systems (OS) or Real-Time Operating Systems (OS) and could be considered.

4.5 RAT Scoring System

Following from the discussions in the previous chapters, the system model needs to be: *User-centric*, *Decentralized*, *Mobility-oriented*, *Traffic oriented*. An equilibrium between multiple characteristics of different network selection mathematical theories is to be found for the system design. A scoring system is used to prioritise and select a given RAT. The RAT scoring process of the MISS system consists of two utility multi-attribute decision making (MADM) approaches, described below. The evolution of the scoring process, from the first to the second, is based on empirical results obtained during testing. It is to be noted that the MISS system can accommodate scoring approaches based on various techniques other than MADM, such as Game Theory.

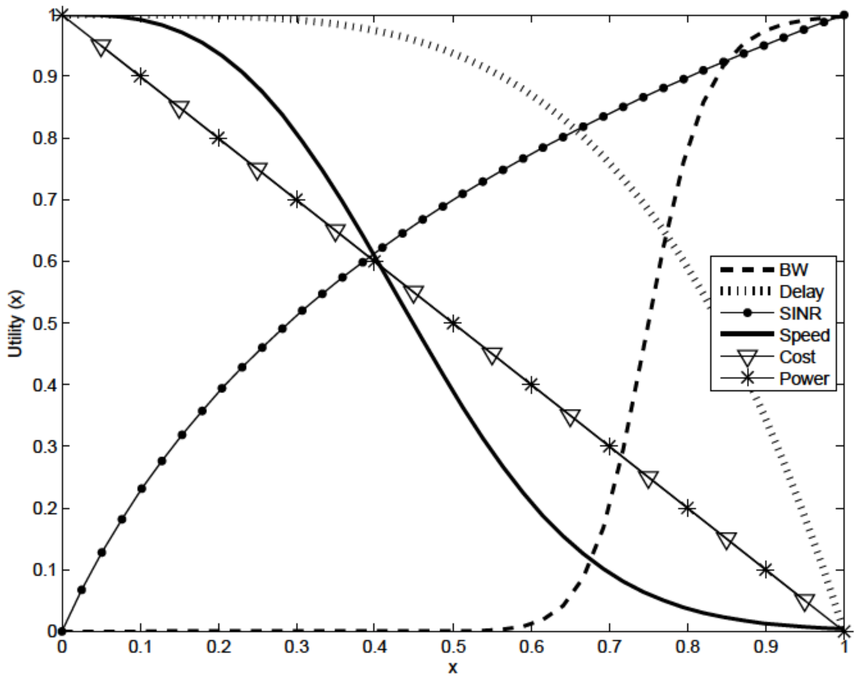


Figure 4.2: Utility Functions

4.5.1 Scoring I

The first score model is based on work reported by Wang et al. [119]. The probability of using a network i, at a certain time, is characterized by a score which is a function of several parameters (P_i).

$$Score_i = f(P1_i, P2_i, ..., Pn_i) \tag{4.5}$$

As mentioned in Section 4.4, six attributes (bandwidth, cost, energy consumption, delay, SINR, and speed of vehicle) are considered for the algorithm.

An example utility model for the six attributes is presented in Figure 4.2. The utility function is needed to scale different parameters with different units to a comparable numerical representation. In this example, it is assumed that the bandwidth follows a sigmoidal function of the form $(x/0.75)^a/[1+(x/0.75)^a]$ where $a = 20$ [120]. Different consumers with different user preferences will have different utility values for the same product as the value a is given based on these preferences [2]. The maximum and minimum values of each attribute are normalised to [0-1].

If the utilities of each parameter ($P1_i, .., Pn_n$) are going to be summed up with equal weights, multiple small attributes for a profile could conceal the importance of the key attribute and dominate the final decision. Weights are therefore added to each parameter $(w_1, w_2 ... w_n)$ where $\sum_1^n w_i = 1$. For those parameters that are less important to the profile, the weights can be set to 0. These weights can be tuned to optimize a particular objective. The lower the weighted score, the more the network is suited to the specified profile. The score of each candidate network i is then obtained by adding the normalized contributions from each metric multiplied by their weight, as shown in equation 4.6. The model design can thus provide the best available QoS at any time, or the lowest cost based on user preference.

In addition to the described model, a network elimination factor can be added [2]. Either 1 or 0, this factor reflects whether current network conditions are suitable for requested applications. For example, if a network cannot guarantee the delay requirement specified for an application, its corresponding elimination factor will be set to zero. Thus, the corresponding score becomes zero, which eliminates that network. Multiple network elimination factors can be added for one application. If there is no elimination factor for the network the value is a constant 1. For the sake of conciseness, three attributes will be modelled, similar to [119]. The weighted score of using network i at a certain time as a function of the bandwidth (B_i), energy (E_i), and cost (C_i) becomes:

$$f_i = e_j^k[(w_b \cdot N(\frac{1}{B_i}) + w_p \cdot N(E_i) + w_c \cdot N(C_i)] \tag{4.6}$$

with $\sum w_n = 1$, N the normalized utility and e_j^k the elimination factor(s) for application k for attribute j. Application k can be divided into four main traffic categories: Background, Voice, Video, Best-Effort. Subcategories of applications, such as High-Quality/Low-Quality, can also be applied.

A general form of weighted score function for the presented network selection problem based on work reported by [121] is as follows:

$$\mathcal{F}_i = \sum_k (\prod e_{ij}^k) \sum_j [w_j^k \mathcal{N}(u_{ij}^k)] \tag{4.7}$$

where e_{ij}^k is the network elimination factor, either 1 or 0, of application k, in network i, in terms of attribute j.(w_j^k) is the weight of attribute j for application k and $\mathcal{N}(u_{ij}^k)$ represents the normalized utility.

4.5.2 Scoring II

The second scoring approach is also based on the previously mentioned six parameters. The novel validation process for a RAT to get a score (S_x) is based on three steps:

1. **Application Validation** (Bandwidth and Delay)
2. **Network Validation** - (SINR and Vehicle Velocity)
3. **User Preference Validation** - (Cost and Energy Consumption)

The score of each RAT (S_x) is used in the scheduler for the distribution of packets across different RATs, as described in section 4.6. Why is the scoring divided in the above mentioned three steps?

1. An application is not concerned about the network on which the data is sent or the user preference.
2. The network path is not concerned about the traffic type.
3. A user is not concerned about the underlying network concepts.

This novel approach is a combination between a compensatory algorithm and non-compensatory algorithm: a compensatory algorithm was adapted by adding minimum cut-off values.

Application Validation - 'The network viewed by the application'

The initial step is to compare the delays and bandwidth of each RAT. If the RAT values do not meet the required reference for a specific application z, the RAT is eliminated. Otherwise, they are validated to the next stage and a score is allocated based on the utility function from Figure 4.3 [25]. The score for the bandwidth (b_{xz}) is limited to a maximum score of 1. In a heterogeneous wireless network environment, when an application requires higher throughput than the individual RATs can provide, the bandwidth offered by the RATs can be aggregated to create a larger logical link with enough bandwidth to meet the desired throughput ($b_1 + b_2 + ... + b_x$) [14]. Depending on the chosen profile, the process can continue in 'best-effort' manner and the packets are sent even if there are no real changes of the messages being received.

At this point the scoring equation is as follows:

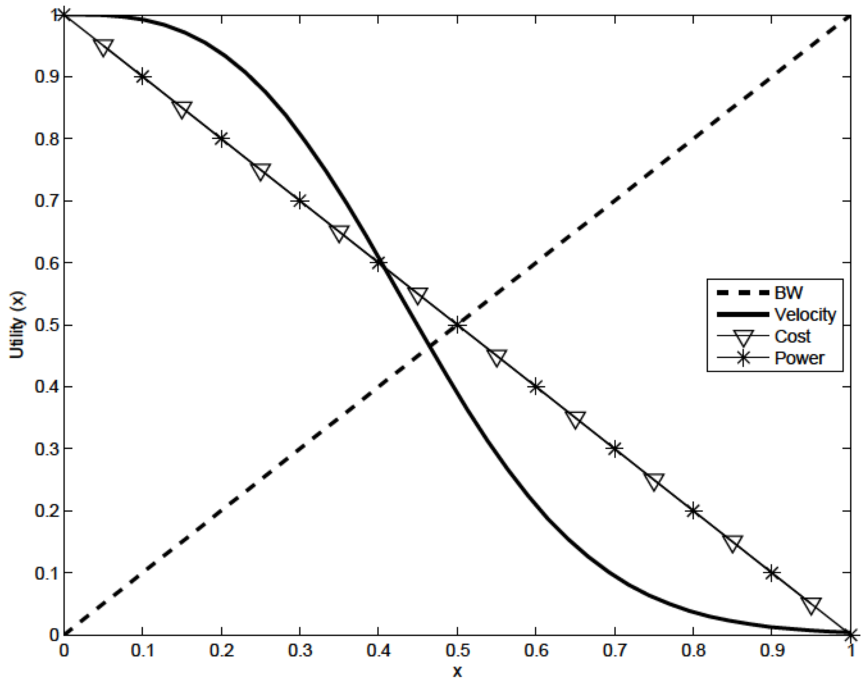


Figure 4.3: Utility Functions with fewer parameters

$$S_{xz} = b_{xz} \tag{4.8}$$

where S_{xz} is the score of RAT x for queue type z.

Network Validation - 'The network viewed by the network'

Another elimination factor is applied for the receiver power, specific to each RAT (i.e. Wi-Fi: -94 dBm; LTE: -140 dBm). If the RATs meet this threshold they continue the scoring system, otherwise, they are eliminated.

The velocity score (v_x) is obtained by using different utility graphs for each technology as it does not have a similar influence on Wi-Fi and on cellular technologies. A velocity score for each RAT is obtained on the specific utility functions and then multiplied with the bandwidth score, resulting in an updated score S_x.

$$S_x = b_{xz} \cdot v_x \tag{4.9}$$

All the RATs that have a score higher than 0 are validated for the next and last stage.

Figure 4.4: Scoring Flowchart of MISS

User Preference Validation - 'The network viewed by the user'

In this last scoring part the different weights and user preferences are taken into consideration. The cost and energy consumption (c_x, e_x) are predefined values for each technology. The cost and energy weights (w_c, w_e) are chosen by the user. If cost is not important for a user, the weight is set to 0, and thus it does not influence the score. If it is considered important, the weight can be set up to a value of 1. These two parameters and their weights define the final score:

$$S_x = b_{xz} \cdot v_x \cdot (c_x \cdot w_c + e_x \cdot w_e) \tag{4.10}$$

As the bandwidth and delay have minimum cut-off values and their scored values are not taken into consideration, the utility function for this second approach has less functions and can be observed in Figure 4.3.

The scoring system is summarized in the flowchart in Figure 4.4.

Table 4.2: Scheduler RAT availability

	RAT 1 (10 Mbps)	RAT 2 (20 Mbps)	RAT 3 (30 Mbps)
Iteration 1	1	1	1
Iteration 2	0	1	1
Iteration 3	0	0	1
Iteration 4	1	1	1
Iteration 5	0	1	1
Iteration 6	0	0	1
...			

4.6 Scheduler

The schedulers' main purpose is to distribute the packets from different queues based on user's choice by responding to QoS standards and safety critical applications. The scheduler is asynchronous to the classification of the packets in the different queues. The scheduler allocates packets to each RAT in proportion to their respective data rates. For instance, if a packet size of 1448 bytes is assumed (prevents fragmentation: MTU of 1500 bytes - 52 bytes for IP overhead), and a RAT data rate of 10 Mbps, the scheduler is recursive every 1 millisecond. For a data rate of 20 Mbps, every 500 microseconds. For a data rate of 10 Mbps, every 250 microseconds. The scheduler always accommodates the RAT with the highest data rate. The other available RATs are marked available ($AvailabilityRAT_x$) based on the remainder from the scheduler iteration counting (it) modulo the ratio of the RAT ($ratio_x$). If the remainder is 0, the RAT is marked available. The ratio of RATx ($ratio_x$) is expressed as the maximum data rate of all RATs over the data rate or RAT dr_x:

$$ratio_x = \frac{max(dr_{x1}, dr_{x2}, ..., dr_{xn})}{dr_x} \tag{4.11}$$

$$\forall x, it \mod ratio_x = AvailabilityRAT_x \tag{4.12}$$

Table 4.2 presents an example with a bit rate of 10, 20, 30 Mbps per RAT 1, 2, 3 respectively. In the case of a non-harmonic scheduler (if the remainder is different to 0), the scheduler can perform under the maximum capacity by adjusting to the lower value or saturate at values higher than 100%. The latter option provides more flexibility as advantage can be taken of the different RATs MAC queue buffering.

4.6.1 Scheduling Algorithm

```
q : queue
z : chosen queue to send packets from
n : number of packets to send
m_z : max packets (%) to send (percent of n)
a : number of available RAT
S_xz : Score of RAT x for queue type z
loop (void)
    calculateSchedulerAvailableRATs()
    queue()
    trafficDistribution(z,n)
    If a ≠ 0,∀q ≠ z, queue();
end loop
function queue(void)
    Check length of each Queue (q)
    if q_safety ≠ 0 then z = q_safety, n ≤ m_safety
    else if q_video ≠ 0 then
        z = q_video; n ≤ m_video
    else
        z = q_x; n = m_x;
    end if
    return z, n
end function
function trafficDistribution(z, n)
    getRATScores(n)
    n → ∀ RATs, S_xz > 0
end function
function getRATScores(queueType)
    Calculate S_xz return S_xz
end function
function bandwidthEstimationFunction(RAT)
    Calculate m_z return m_z
end function
```

*→ :to be read as *'send on'*

Figure 4.5: MISS Scheduler Algorithm

The example scheduling algorithm presented in Figure 4.5 has the following procedure:

1. Determine the number of available RATs for each iteration.
2. Determine the queue type to send packets from (z) and the number of packets to send (n).
3. Calculate the score (S_x) of each available RAT for the retrieved queue (z).
4. Packets are sent on the available RATs with $S_x > 0$.
5. If there are available RATs remaining for that iteration, the process is repeated for the lower priority queues (only for Parallel Transmission Profiles).

4.6.2 Different User Policies

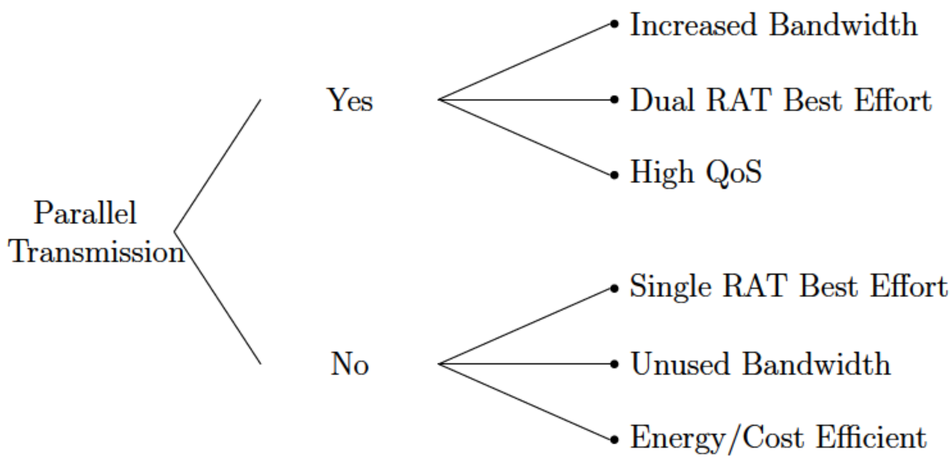


Figure 4.6: Examples of User Profiles and their use of parallel transmission

Different policies influence the scoring system and in consequence the distribution of packets at the scheduler. These policies are defined by the user profiles, thus influencing the transmission schemes and the scheduler. The user specified relative importance can influence the cost and energy scoring of the system. These parameters do not have an influence on the safety critical messages if there is only one RAT that can accommodate the messages.

A non exhaustive list of some of the user profiles that can be used in the shim layer can be found in Figure 4.6. If the profiles are combined they can become even more complex, for instance providing access with a High Priority and Cost

Effective profiles. The most stringent requirement will take over and thus only a single RAT may be used, unless safety messages are involved - further described in section 4.6.3.

4.6.3 Parallel Transmission

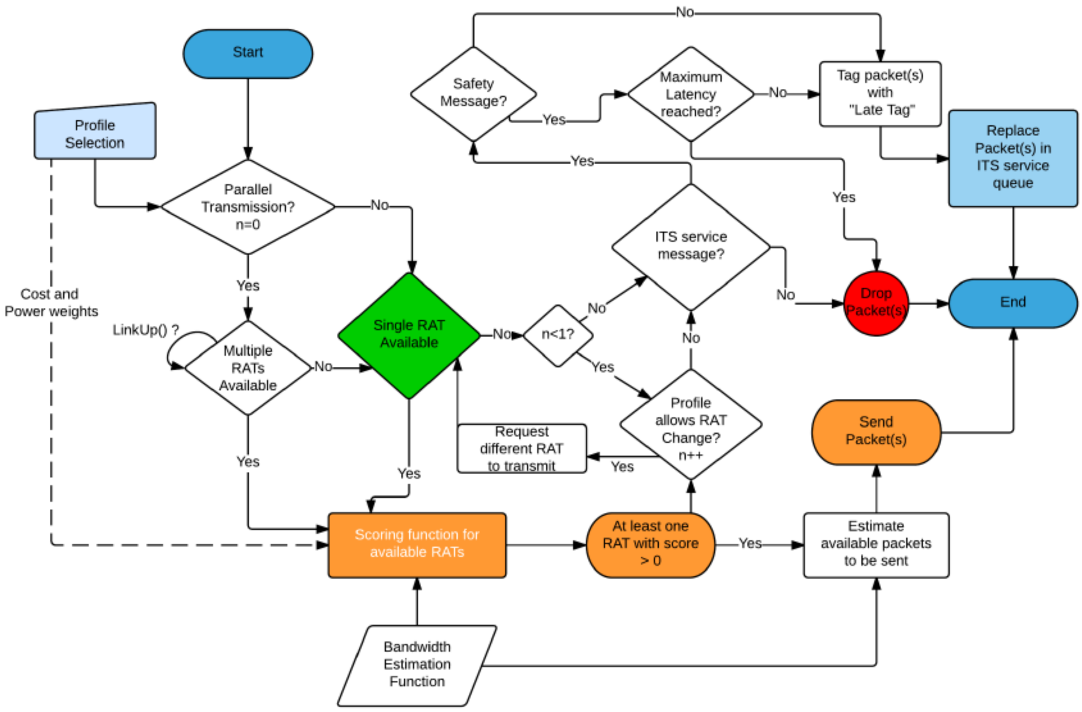


Figure 4.7: Parallel Transmission Flowchart

Depending on the selected profile or the type of transmitted messages, the scheduling algorithm might use a parallel transmission of packets on multiple RATs. The parallel transmission mechanism flowchart (Figure 4.7) is part of the 'Scheduler' and is RAT independent. This process is performed for each iteration of the algorithm. As described in the previous section, the user profile selection influences the scoring of each RAT and the possibility of using multiple RATs. The dotted line indicates a link that does not occur for each iteration. The 'Scoring Function' is informed of the 'Cost and Energy Weights' only when these values change. The 'ITS Service Message' consists of all the ITS messages described in Section 2.4. Some of these messages are not considered as 'safety' and could therefore be placed in a queue other than the 'Safety queue'. If the receiver can make timely use of delayed messages, the packets should be queued for transmission. For instance, an 'Ice Warning' alert can be beneficial but an 'emergency electronic brake lights' might not. The packets are tagged with the 'Late Tag' and replaced in the safety queue for retransmission even if their chances of arrival to the destination are low (no RATs meet the required performance criteria). These re-queued safety packets will be discarded by the shim layer queue if the delay value exceeds a predefined threshold or if the packets expire. The 'RAT change' scenario is only active if a non parallel transmission profile is chosen.

4.7 Summary

In this chapter, all the agents of the MISS scheduling system have been described and the relation between them analysed. The three most important agents are the 'Scheduler', the 'Scoring System' and the 'Bandwidth Estimation Function'. The algorithm approach is a combination between a compensatory algorithm and non-compensatory algorithm: a compensatory algorithm is adapted by adding minimum cut-off values. The user profile choice outputs values for the scoring system, in terms of allocated weights to the cost and energy consumption scoring attributes. It also influences the parallel transmission decision by indicating if multiple RATs can be used by the node. Parallel transmission may be preferable if two or more RATs are available, there is a need for bandwidth aggregation or for certain safety critical message types.

Chapter 5

MISS Evaluation

"and the life which is unexamined is not worth living"

[Socrates][Plato's Apology, (38a)]

5.1 Introduction

In this chapter the work carried out to simulate the performance of the shim layer in saturated and non saturated non cooperative traffic environments, with a single user and multiple users is presented. Large-scale experimental test beds are too expensive and complex while comprehensive analytical approaches are often untraceable from a mathematical viewpoint [7]. Discrete event simulation (DES) is therefore the most suitable approach for performance evaluation of large networks. The simulation tools available and the important characteristics to be taken into account are described in Section 5.2. The full performance evaluation of the shim layer and algorithm has been evaluated in various published papers [24] [25] [27]. In Section 5.3.2 the shim layer concept is introduced and its function demonstrated [24]. In Section 5.3.3 it is shown that the shim layer can improve video delivery quality by prioritizing the most important frames [27]. This study is an extension to the previous work, described in [25], where it is demonstrated that the shim layer can prioritize safety messages regardless of the level of saturation of the link. Finally, in Section 5.3.4 a non-cooperative multi-user approach is studied.

5.2 Simulation Software

Some of the most commonly used network simulators are ns-2, ns-3, OMNeT++, OPNET, QualNet and SWANS [122]. All are discrete-event simulators which means they are well suited to simulating packet transmission across a network, but do not have integrated vehicular mobility traces. The road traffic dynamics are the most distinctive feature that tells vehicular environments apart from other mobile scenarios. The movement of vehicles can dramatically affect the behaviour of network protocols [123] and an incorrect representation of car traffic can lead to misleading performance results and wrong conclusions, even if the network-level simulation is flawless [7]. A traffic trace generator/simulator, such as SUMO (Simulator of Urban MObility)[1], is needed for realistic vehicular mobility traces. Three performance indicators represent vehicular traces: velocity of the nodes (km/h), density (vehicles/km) and flow (vehicles/h). One of the major publicly available vehicular mobility traces is from the city of Cologne (Germany) with 770,000 monitored vehicles for a 24 h duration, covering all roads on an area of 400 km^2 [124]. Turin (Italy), Luxembourg (Luxembourg) and Zurich (Switzerland) are also some of the cities that have mobility traces and are popular amongst simulators. A summary table is described by Beylot et al. [7].

The compatibility between the network simulator and the mobility traces depends on the ITS scenario. In an ITS scenario where the mobility is influenced by the communication result (e.g. accidence avoidance, congestion reduction), an integrated case is used. Otherwise, in an ITS scenario where the mobility does not need to be influenced by the vehicular communications (e.g. data collection from vehicles, traffic updates), an isolated case is used.

Integrated case - iTETRIS [125] is an open-source intelligent transportation system simulation platform that integrates SUMO with ns-3 and allows the implementation of cooperative ITS applications in various programming languages. OMNET++ and SUMO were also combined to create the very popular Veins (Vehicles in Network Simulation) [126]. Both iTETRIS and Veins simulate traffic flow dynamically and Inter-Vehicle Communications (IVC). VSimRTI [127] additionally extends the combined SUMO/ns-3 by including user be-

[1] `https://sourceforge.net/projects/sumo/` - [Accessed: 2016-08-11]

haviour to create an even more comprehensive and complete simulator.

Isolated Case - The isolated case extracts synthetic traces from the traffic simulator (SUMO) in the shape of mobility files that are later integrated into the network simulator. The communication between vehicles does not change the mobility of the nodes.

5.2.1 ns-3

The choice of the network simulator is ns-3. The advantages are that it is modular, open-source and there is a large active online community. In addition, ns-3 has more detailed models in several popular areas of research (including sophisticated LTE and Wi-Fi models), and its open support of implementation code provides a very wide spectrum of high-fidelity models. The entire Linux networking stack can also be encapsulated in an ns-3 node, using the Direct Code Execution (DCE) framework, which can be a useful feature for algorithm implementation in hardware.

One of the disadvantages of ns-3 is that the physical layer and channel models operate on a per-packet basis, with no frequency-selective propagation or inter-channel interference effects. There is interference between nodes within a same channel or LTE cell but there is no cross-channel, cross-cell interference. Detailed link simulations are not performed, nor are frequency-selective fading or interference models available. Directional antennas and MIMO are also not currently supported. Radio performance is governed by the application of analytical models (based on modulation and factors such as channel width) to the received signal-to-noise ratio, where noise combines the effect of thermal noise and of interference from other signals on the same channel. Radio frequency interference from other technologies is not modelled.

As previously described in Chapter 3, a new ns-3 model was developed for the proposed shim layer and scheduling algorithm that can integrate transparently with the existing ns-3 RAT models.

5.2.2 Performance Metrics for System Evaluation

As previously described in Section 4.5, the system needs to meet the following requirements: *User-centric*, *Decentralized*, *Mobility-oriented*, *Traffic oriented*. The performance metrics of interest for the evaluation of the shim layer that can have the system meet the requirements are as follows:

End to End Delay (Latency) - the sum of all mean delays for each vehicle, normalized over the total number of flows in the network, where mean delay is defined as the ratio between the sums of all delays in the end to end path and the total number of received packets [72]. The *queue delay* is included which is the average duration of time spent in the transmission queue for a packet. This is important for the prioritization of Safety Messages.

Packet Delivery Ratio (PDR) - calculated as the ratio between the number of received packets and the transmitted packets.

Throughput - the sum of received data frame bytes at the destinations, averaged over the total number of flows in the network.

Video Evaluation - Quality of Service/Experience - According to the ITU (International Telecommunication Union), the Quality of Service (QoS) is "the totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service" [128]. According to the same ITU, the Quality of Experience (QoE) is "the overall acceptability of an application or service, as perceived subjectively by the end user" [129]. The two are thus linked and a good set of QoS indicators is likely to improve the QoE of the users. There are three possible models for measuring QoE according to Kuipers et al. [130]:

- The no-reference model has no knowledge of the original stream or source file and tries to predict QoE by monitoring several QoS parameters in real-time.
- The reduced reference model has some limited knowledge of the original stream and tries to combine the limited knowledge of the original stream with real-time measurements to reach a prediction on the QoE.
- The full reference model assumes full access to the reference video, possibly combined with the measurements conducted in real-time environment.

In terms of video evaluation, there are two measures commonly used for measuring the performance:

- Mean Opinion Score (MOS) scale, based on complex subjective tests, are often not afforded.
- Calculation of Peak Signal to Noise Ratio (PSNR) image by image. The method is part of the objective metrics that have been developed to emulate the quality impression of the Human Visual System (HVS) to respond to the numerous tasks in industry and research that require automated

methods to evaluate video quality [131]. This is a derivative of the Signal to Noise Ratio (SNR), which compares the level of received signal to the levels of noise. The PSNR compares the maximum possible signal energy to the noise energy, which has shown to result in a higher correlation with the subjective quality perception than the conventional SNR [132]. EvalVid [131] is an offline evaluation tool for measuring QoE with PSNR values. Because of its modular structure, EvalVid makes it possible to select both the underlying transmission system as well as the codecs, so it is applicable to any kind of coding scheme, and can be used both in real experimental set-ups and simulation experiments.

The shim layer is evaluated for each of these performance metrics in the following sections.

5.3 Experiments

The 'Experiments' section is divided in four subsections. Each subsection introduces the objectives of the simulation, the environments and the methodology used. Section 5.3.1 ('Assumptions') is valid for all the experiments.

The first set of experiments (Section 5.3.2) aims to prove that the system model is correct and that the MISS model responds to the different parameters/profiles taken into consideration. A single user with a single queue is used; there is no prioritization of safety messages yet. Throughput is the performance metric of interest for this section.

In the second set of experiments (Section 5.3.3) a single user with a multiple queue shim layer is assessed for prioritizing safety messages. The MISS prioritization aspect is also tested to assess the performance and improvement of QoS and QoE of streamed images by using the EvalVid framework.

In the third set of experiments (Section 5.3.4) the full feature shim layer (multiple queues, safety messages prioritization) is assessed in a non-cooperative multi-user environment where the number of users varies. The objective is to show that the shim layer can keep a high packet delivery ratio even in crowded saturated environments.

The end-to-end delay is assessed in both second and third experiments (Sections 5.3.3 and 5.3.4 respectively). Additional work on this performance metric is described in Chapter 6.

5.3.1 Assumptions

As previously mentioned in Chapter 3, even though the shim layer works for both uplink and downlink, the user perspective approach of the uplink is the only one addressed. A single path is used for downlink. The focus is set on the uplink, rather than the downlink, as several emerging applications treat vehicles as data sources in mobile sensor networks, where a variety of sensors (GPS, cameras, on-board diagnostics) acquire and deliver data about the surrounding environment [79]. The uplink model does not require any changes to the current infrastructure as the packets are forwarded to the Base Station/Access Point and from then on the packets follow a standard route to the destination. The downlink operator side would require the router in the cloud to have a table specifying the number of interfaces/technologies each user has, check their availability, and redirect the packet to one of the users' points of attachment (BS/AP) to the network.

5.3.2 Validation: Throughput - Single Queue

The objectives of this first set of simulations are to demonstrate the feasibility and transparency of scheduling on a packet by packet basis at the shim layer and to show that the sent/received packets are symmetrical with respect to the score function and chosen transmission scheme.

The Multiple Interface Scheduling System (MISS) presented in Chapter 4 with the algorithm from Figure 4.5, has been implemented in the shim layer (Chapter 3). This scheduling algorithm is based on the transmission schemes and scoring model presented in Section 3.3.3 and Section 4.5.1. The profile selected by the user will determine the attribute values (j) for application (k) and the priority of usage of the different schemes. These values are stored as a table accessible by the shim layer. For each incoming packet from the upper layer (IP layer), the scoring system outputs a score for each of the RATs with the latest known parameter values. The packet by packet approach and score calculation responds to rapid changes in the characteristics of the link but does require higher computational power compared to a block processing of packets.

The different transmission schemes presented in Section 3.3 are assessed. If scheme A (Parallel without Redundancy) is selected, all the networks that have a score higher than 0 are used for transmission. The packet count (p_t) decides which RAT sends the packet (line 5 of Figure 4.5: $t \mod x = i, p \rightarrow RAT_i$). If scheme B (Parallel with Redundancy) is selected, the same packet is sent on all the networks that have a score higher than 0. Lastly, if scheme C (Switched) is

Table 5.1: Single User Model Validation ns-3 Simulation Setup

	Wi-Fi ① ●	**Wi-Fi ②** ●	
RAT	802.11n	802.11n GHz	
Frequency	2.4 GHz	5.18 GHz	
Data Rate	21.9 Mbps	27.1 Mbps	
Link Delay (Fixed)	20 ms	10 ms	
APs	1	1	
Propagation Loss Model	FSPL	FSPL	
Queue Type	FIFO	Data Traffic	[20;40;60] Mbps
Transmit Power	20 dBm	Packet Size	1500 bytes
Number of nodes	1	Receiver Sink	1
Node speed	5 m/s	Transport Layer	UDP
Mobility	Predefined	Network Layer	IPv6
Coverage	Continuous	Addressing	Static
Simulator	ns-3.18	Simulation Time	10 s

selected, the packet is sent on the RAT that has the maximum score.

Simulation Environment

The simulation parameters are presented in Table 5.1. Two types of network technologies, 802.11n 2.4 GHz and 802.11n 5.15 GHz, each with 20 MHz channel bandwidth, have been simulated as an example of a heterogeneous environment. These have been selected as they are the most widely deployed Wi-Fi access technologies in dense urban environments. The standard theoretical rate for both technologies is 54 Mbps but the effective simulated maximum payload throughput with ns-3.18 is 21.9 and 27.1 Mbps respectively. This is linked to the transaction model (Distributed Interframe Space (DIFS), Short Interframe Space (SIFS), and 802.11 ACKs) and the encapsulation of the frames. A full explanation is given by Matthew Gast in [133] or [134]. The received power for the two RATs is presented in Figure 5.3, with an assumed transmission power of 20 dBm (100 mW) with a Free Space Path Loss (FSPL) propagation model. The FSPL was chosen since the primary goal is to demonstrate the functioning of the shim layer and not focus on the other wireless technology aspects that

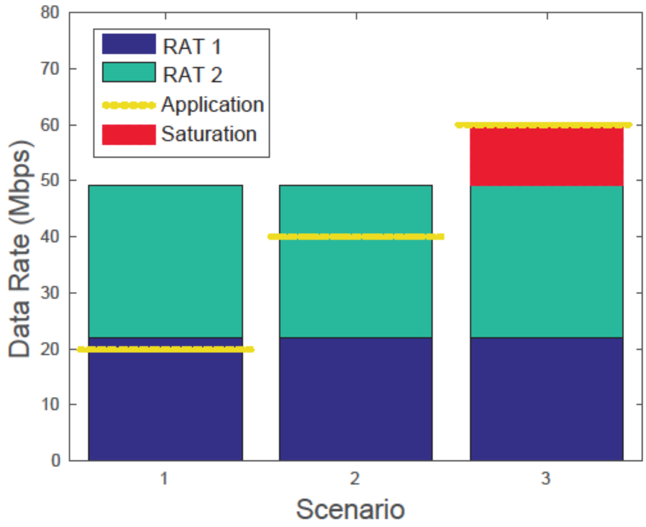


Figure 5.1: Data rate scenario description and capacity per RAT

could influence the results. The FIFO queue was chosen for the same reasons. The two Access Points (AP) are 50 m apart and a node (vehicle) moves linearly from AP 1 to AP 2 at a constant speed of 5 m/s, where AP 1 is the start point and AP 2 is the destination point. Both APs are linked to a sink that receives and monitors all the packets. RAT 1 is associated with AP 1 and RAT 2 with AP 2. The simulated scenario is shown in Figure 5.2.

The node transmits at data rates of 20/40/60 Mbps. Each of these data rates has a data rate scenario associated, summarized in the stacked bar chart plot in Figure 5.1. The rates have been chosen to have all possible combinations in terms of availability and capacity of the different RATs. In Scenario 1, each of the RATs can transmit the entire data rate (20 Mbps) as it is below their respective maximum throughput (21.9 Mbps and 27.3 Mbps). In Scenario 2, the 40 Mbps can be achieved only if the two RATs are used cooperatively ($21.9 + 27.3 = 49.2$ Mbps). Finally in Scenario 3, both RATs are saturated as they can not meet the required data rate even if they respective data rates are combined.

The simulation values for the attributes are presented in Table 5.2, adapted from Wang et al. [2]. The cost for both technologies are considered to be equal (5) and the energy consumption of both technologies are also considered to be equal (50). The delay (x) and SINR (y) are the two attributes that are varying in the scenario. The weight factors of the different parameters are also presented in the same table, with delay weighting twice as much as SINR. A similar table

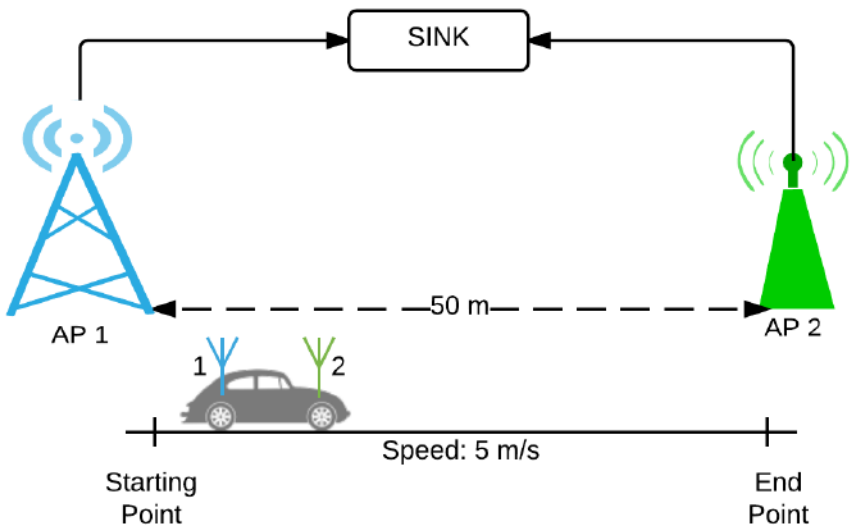


Figure 5.2: Simulated Scenario for Validation Throughput

was used as an example in Chapter 4.

It is assumed that there is no interference and noise in the scenario and thus the SINR is equivalent to the received power, as shown in Figure 5.3. The threshold for a successful transmission, and elimination factor for SINR, has been arbitrarily set to a value of -50 dBm. It is assumed that a device under coverage of more than one RAT is able to use all resources. In the region where the received power from both APs is greater than -50 dBm, corresponding to a range of 20 meters to 30 meters using the FSPL model, packets can be transmitted over both RATs. The delay is assumed to be constant for both RATs: 20 ms for RAT 1 and 10 ms for RAT 2. This delay distribution will illustrate the scoring function and how the scoring influences the RAT transmission in scheme C (switched).

Table 5.2: Selected Attributes and Weights

	Bandwidth (Mbps)	Cost -	Energy -	Speed (m/s)	Delay (ms)	SINR (dBm)
RAT 1	54	5	50	5	x_1	z_1
RAT 2	54	5	50	5	x_2	z_2
Weight	0.1	0.1	0.1	0.1	0.4	0.2

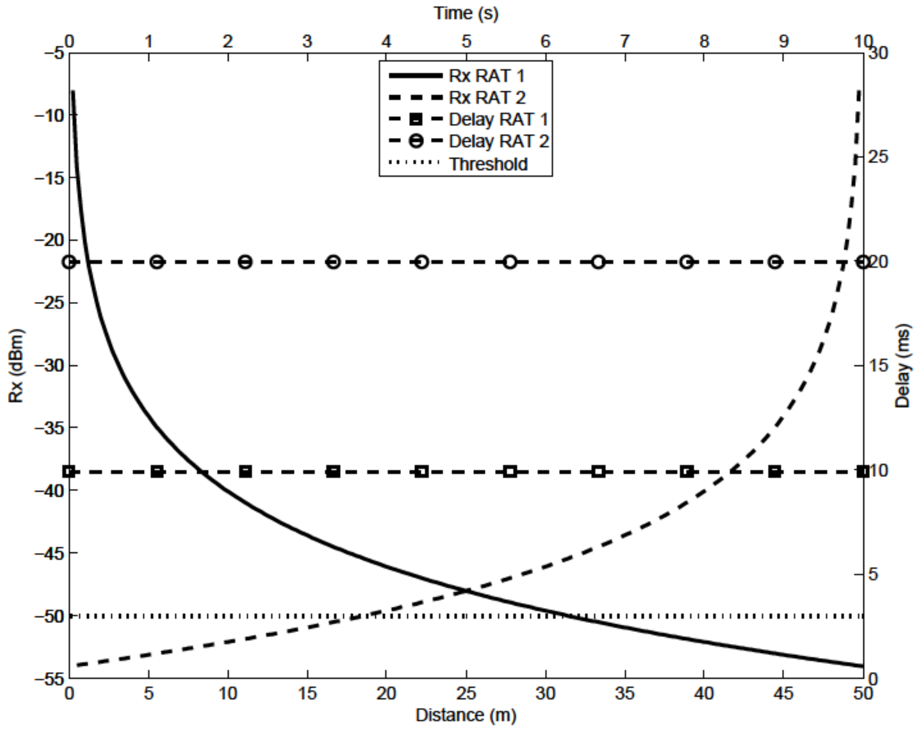


Figure 5.3: Received Power and Delay Assumption

Results

The simulation results are presented in Figures 5.4, 5.5 and 5.6. Each figure represents a change in the transmitted data rate. As a reminder from Chapter 3:

- Scheme A: Parallel without Redundancy
- Scheme B: Parallel with Redundancy
- Scheme C: Switched

The figures plot the received number of packets per second for the sink and the sent number of packets per second for the sender (RAT 1 and RAT 2). Table 5.3 shows the average throughput, at the physical layer, for the receiver at the sink and for each individual RAT on the sender. It can observed that:

1. The average received throughput at the sink for the 40 Mbps data rate in scheme A is 8.8% higher compared to Scheme C (30.079 Mbps - 26.561 Mbps). This can be seen on the graphs in Figures 5.5(a) and 5.5(c).
2. In the 40 Mbps and 60 Mbps scenarios, it is important to note that even if the average data rate at the sink is almost identical for schemes A and

Table 5.3: Average Data Rate Results for All Three Schemes

	Average Data Rate (Mbps)			
	Data Rate	Sink	RAT 1	RAT 2
	20 Mbps	20.857	16.617	16.628
Scheme A	40 Mbps	30.079	16.301	21.996
	60 Mbps	32.374	28.064	22.765
	20 Mbps	26.22	20.887	20.905
Scheme B	40 Mbps	32.405	18.147	22.766
	60 Mbps	32.374	28.064	22.765
	20 Mbps	20.857	20.887	20.923
Scheme C	40 Mbps	26.561	18.147	22.801
	60 Mbps	26.558	28.063	22.801

B, half of scheme B packets are duplicates since the scheme is Parallel with Redundancy and the packets are duplicated at the Shim Layer before being sent on the second RAT. The goodput for scheme A is therefore higher than scheme B.

3. The MAC header adds an extra 48 bits which explains that the received throughput of 20.857 Mbps at the sink for Scheme A is higher than the sent data rate (20 Mbps).

The following observation can be made from the 20 Mbps scenario (Figure 5.4):

1. The sink receives at a constant rate for both Schemes A and C, even if there is a switch in the transmitting RAT technology on the sender side.
2. For scheme A, during the period of time when both RATs are in transmission range, the sent data is divided equally between the two RATs - Figure 5.4(a).
3. This is not the case for Scheme C where the RATs are individually transmitting either the entire data rate (20 Mbit/s) or none - Figure 5.4(c).

The 40 Mbps scenario (Figure 5.5) allows the following observations:

1. The packets are more evenly distributed, similar to a load balancing scheme, over the two RATs when used cooperatively (scheme A) rather then when used separately (scheme C).

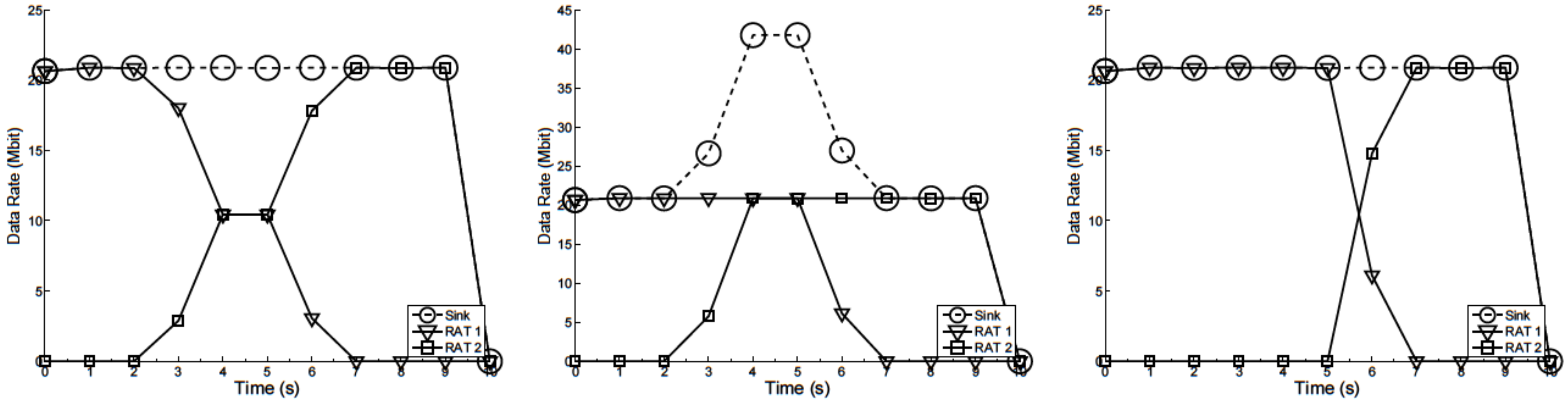
2. Scheme B for 40 Mbps (Figure 5.5(b)) is not efficient as it sends the same number of packets as the 60 Mbps scenario (Figure 5.6(b)). This can nevertheless be of interest for delay sensitive applications, as the packet arriving first can be taken into account and the second discarded.

3. Scheme C is less efficient in terms of received throughput compared to schemes A and B.

In the 60 Mbps scenario (Figure 5.4), which is the full saturation, the following analysis can be made:

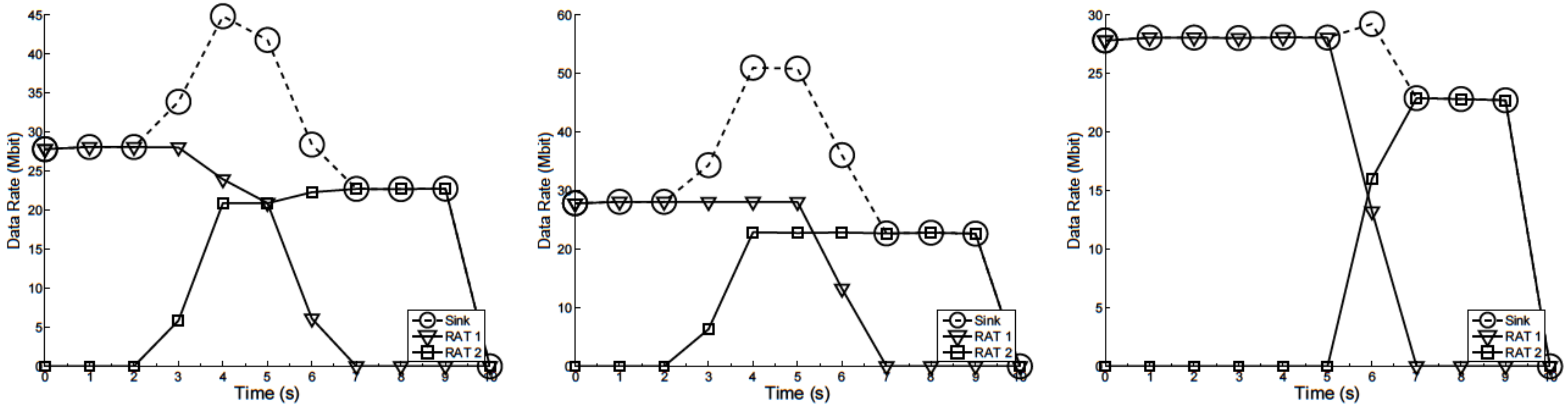
1. The peak occurring in Figures 5.5(c) and 5.6(c) of scheme C is explained by the saturation of the transmission MAC queue. Even though the algorithm has stopped sending data on RAT 1, due to the MAC buffer overflow, the RAT keeps transmitting the packets left in its MAC queue, thus resulting in the two RATs being used similar to the parallel without redundancy scheme (A).

2. In scheme C even if the received power is higher for RAT 2, RAT 1 keeps transmitting while being above the received power threshold. Based on the received power and delay settings (Figure 5.3) the received power of RAT 2 is higher after a 25 m distance (or 5 s in the simulation). The shim layer should switch from RAT 1 to RAT 2. However, it only switches 1 s later. The delay for RAT 1 (10 ms) is lower than the delay of RAT 2 (20 ms) and the weighting is higher for the delay than the received signal (Figure 5.2) - 0.4 compared to 0.2. The delay weight influences the overall score of the RAT and the packets are continuously being sent on the RAT with the highest score (RAT 1), even if the received power of RAT 2 is higher. This shows that the shim layer weighting is effective.



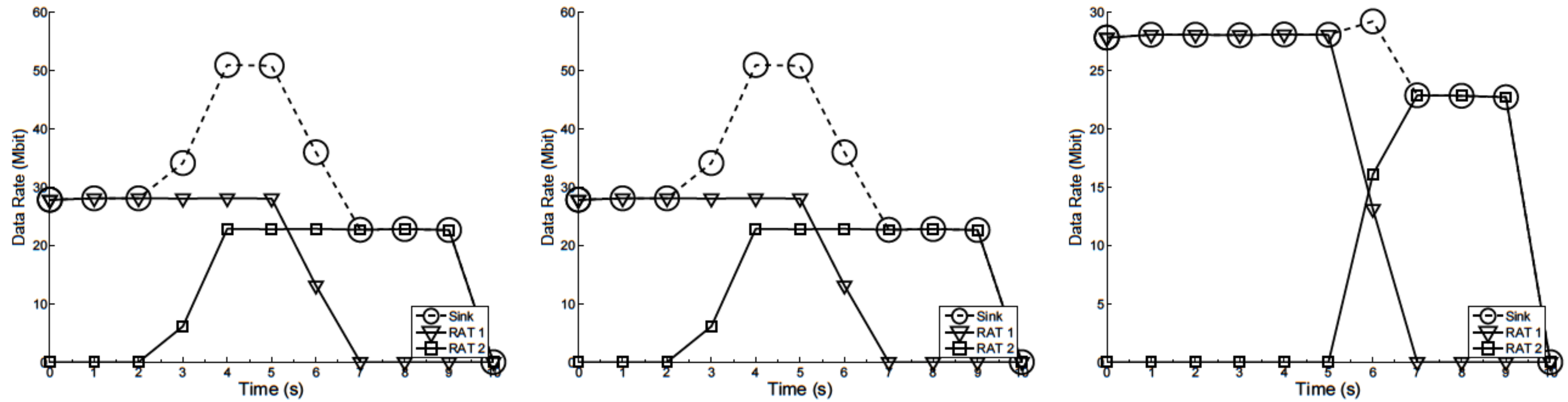
(a) Scheme A: 20 Mbps (b) Scheme B: 20 Mbps (c) Scheme C: 20 Mbps

Figure 5.4: Shim Layer results and behaviour with 20 Mbps transmission rate



(a) Scheme A: 40 Mbps (b) Scheme B: 40 Mbps (c) Scheme C: 40 Mbps

Figure 5.5: Shim Layer results and behaviour with 40 Mbps transmission rate



(a) Scheme A: 60 Mbps (b) Scheme B: 60 Mbps (c) Scheme C: 60 Mbps

Figure 5.6: Shim Layer results and behaviour with 60 Mbps transmission rate

Table 5.4: Prioritising Packets / Multiple Queues ns-3 Simulation Setup

	Wi-Fi ① 🟢	Wi-Fi ② 🔵	Wi-Fi ③ 🟡
RAT	802.11p	802.11n	802.11n
Frequency	5.9 GHz	2.4 GHz	5.18 GHz
Transmission Rate	6 Mbps	21.9 Mbps	27 Mbps
Link Delay	2.40 ms	1.73 ms	1.70 ms
APs	1	2	2
Propagation Loss Model	Two-ray	Two-ray	Two-ray

Queue Type	CoDel	Safety Traffic	10 kbps
Transmit Power	20 dBm	Video Traffic	Various
Number of nodes	1	Voice Traffic	0.3 Mbps
Node speed	5 m/s	Background Traffic	0.3 Mbps
Mobility	Predefined	Best-Effort Traffic	0.3 Mbps
Coverage	10 s/section	Packet Payload	1448 bytes
Receiver Sink	1	Transport Layer	UDP
Addressing	Static	Network Layer	IPv6
Simulator	ns-3.22	Simulation Time	70 s

5.3.3 Multiple Queues - Prioritization of Safety Critical Messages - Video Evaluation - Profiles

After demonstrating the feasibility and transparency of scheduling at the shim layer in the previous section, the objectives of this new set of experiments is to show that a multi-queue multi-RAT approach can respond to the prioritisation of safety critical messages in vehicular networks and to show the benefit of using specific profiles in terms of video QoS and QoE. Video has been chosen as a mean of test as it can assess more easily both QoS and QoE compared to the other queue types (safety, voice, background and best-effort traffic).

The algorithm in this section is tailored for a multi-queue, multi-RAT vehicular environment where the selection of access technology is based on the user perspective. In general, unless otherwise mentioned, it is set with the following priorities:

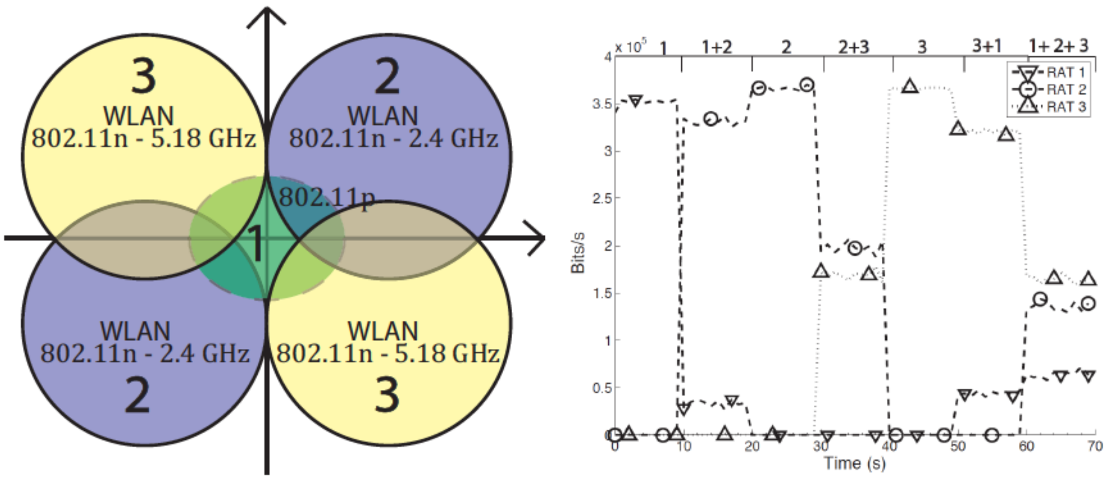
(i) while up to three safety packets, one on each RAT, can be sent for one scheduler iteration, up to two video packets can be sent at a time and only one of the remaining queue types.

(ii) The priority queue operates in a greedy way as long as the safety queue is not empty.

(iii) Only when the safety queue is empty, the other queues will be served and the algorithm becomes a weighted fair queuing.

The simulation environment being considered is shown in Figure 5.7(a) and the simulation parameters and values are presented in Table 5.4. The node travels at a constant speed (18 km/h = 5 m/s), similar to the Brookes ITS vehicle, further described in Chapter 6. The node's predefined route passes through the different coverage areas (①,②,③) and was chosen to have all possible coverage combinations (①, ①+②, ②, ②+③, ③, ③+①, ①+②+③). As a result the coverage environment is continuously changing, every 10 seconds in this case. The 'Two-Ray' propagation loss model predicts the path loss of a received signal from the line of sight transmission and a single ground reflected wave. No buildings or vertical reflections were assumed in the simulation and thus the 'Two-Ray' propagation loss model was selected for all RATs. VoIP traffic was set to 0.3 Mbps in spite of the low traffic produced by VoIP (11 kbps for each direction). It was assumed that video conference calls (e.g. Skype) are tagged as VoIP Traffic rather than Video Traffic since the target application in this work is automated driving in ITS: video is transmitted real-time from a vehicle to a control centre for remote-image processing, as described in Chapter 6. Background Traffic and Best-Effort Traffic have been set to the same data rate (0.3 Mbps) to be consistent when calculating the average data rates with the prioritisation algorithm. The packet payload size of 1448 bytes was chosen to avoid fragmentation at the IP layer (1500 bytes MTU - 52 bytes IP header). The link delay is an empirical value measured during the simulations.

The different RATs available at a given time in the scenario are represented with the numbering at the top in Figure 5.7(b). A single traffic type with a data rate of 0.3 Mbps is transmitted from the node. The plotted values include the headers from the different layers (e.g. IP/MAC layer headers). As a consequence the monitored sent data rate is higher than the application 0.3 Mbps data rate. The transparent switching, with no lost packets, and distribution of packets across multiple RATs can be observed. For instance, when the vehicle is in range of two RATs that have close parameters, and thus similar scores, such as RATs 2 and 3, the algorithm reacts as a load balancing mechanism (section *'2+3'*). However, the main goal of network selection is to always select the best



(a) Simulation Scenario (b) RAT Distribution Scenario

Figure 5.7: Illustration of Simulation and RAT distribution scenario

network for serving the given application and not focus on load balancing [2]. Taking two RATs both with low but totally different traffic loads, the load balancing process ignores the two RATs' low traffic loads but retains only the relative large difference between the two. This leads to excessive traffic load balancing between the two networks and compromises the importance of other attributes. The following set of experiments show that the MISS algorithm is capable of distinguishing between different service types and does not react as a simple load balancing algorithm.

Prioritization of Safety Critical Messages

In a vehicular environment, safety critical information needs to have priority over all other traffic types. In this section the queue selection always accommodates the safety critical queue. If this queue is empty, the other queues are chosen, in the following order: video, voice, best-effort and background.

The following set of results aim to show the improvement in delay and throughput for safety critical traffic obtained in a scenario where the vehicle has access to all three RATs and where the data rate is gradually increased until the channel/medium is saturated (above 54.9 Mbps - combination of the data rate of the 3 RATs). This is performed by increasing the video traffic data rate on the user side. The packet size for the safety critical messages is 150 bytes. The calculated end-to-end packet delay of Figures 5.11, 5.10, 5.12, represent values of successful received packets.

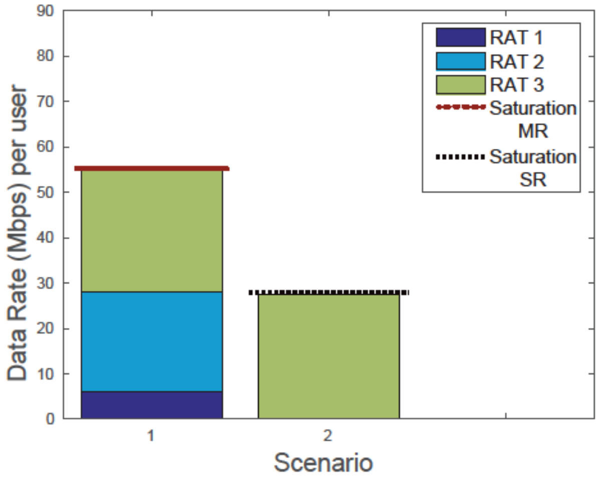
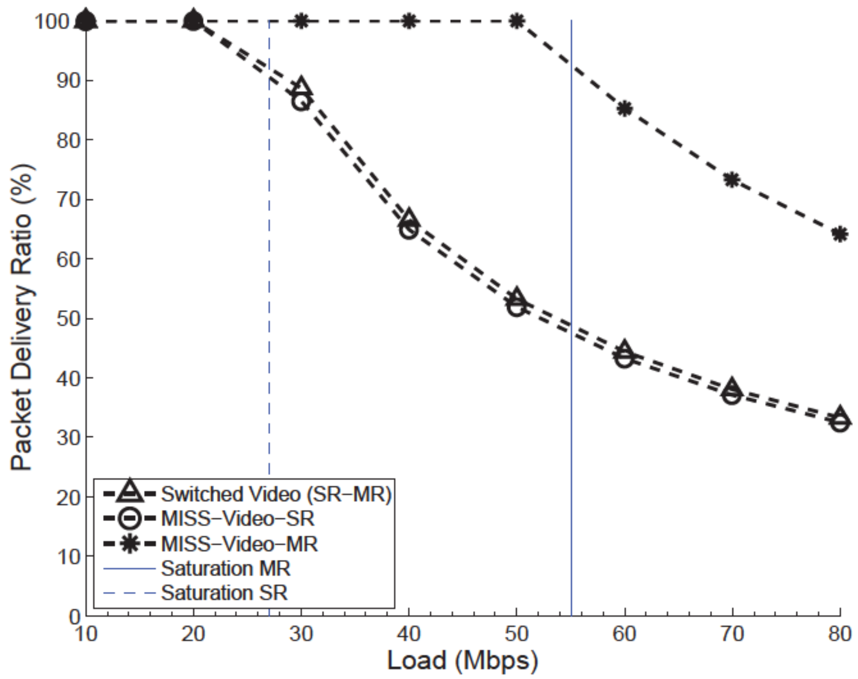


Figure 5.8: Definition of Multi-RAT and Single-RAT Saturation thresholds per user for the prioritization of Safety Messages experiments

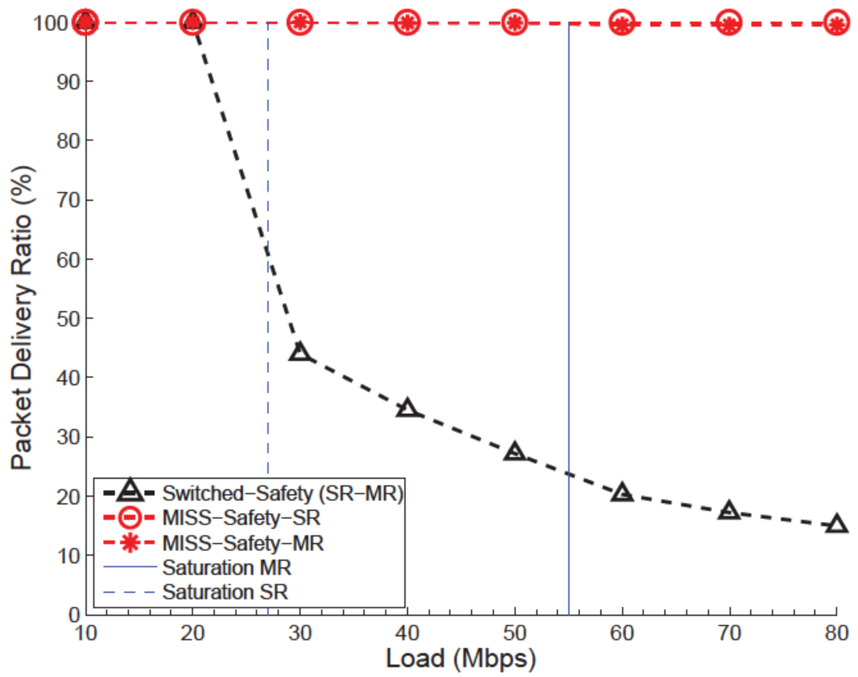
Figure 5.9 depicts the Packet Delivery Ratio (PDR) versus load for both video and safety packets and it can be observed that the packet delivery ratio considerably decreases with the Switched Scheme once saturation of a Single RAT (SR) is reached. The Saturation Multi-RAT (MR) corresponds to the saturation point of the combined radio access technologies (54.9 Mbps - Scenario 1 in Figure 5.8). The MISS algorithm provides a 99.9% delivery ratio of safety messages in both single and multi RAT environment, saturated or not. For the switched scheme, due to the single queue and the difference in the number of transmitted packets between the safety and video packets, the packet delivery ratio for the safety messages is lower than the video ones.

In Figure 5.10 the proposed algorithm is compared to a standard switched scheme where only one RAT is used at a time, for the video (Figure 5.10(a)) and safety traffic types (Figure 5.10(b)). The rest of the traffic types are not plotted since they are not transmitted after saturation (Scenario 1 in Figure 5.8). The results in Figure 5.10(b) show that the end-to-end delay for both safety and video packets is greatly improved compared to a switched approach for a load that exceeds the capacity of a single RAT.

In Figure 5.11 the average end to end delay with a MISS system for different traffic types is plotted in a scenario where multi-RAT saturation is not reached. The safety critical delay remains constant while the other traffic types are affected by the load, demonstrating the efficiency of the algorithm. The background traffic stops after a 30 Mbps load because no packets are received.

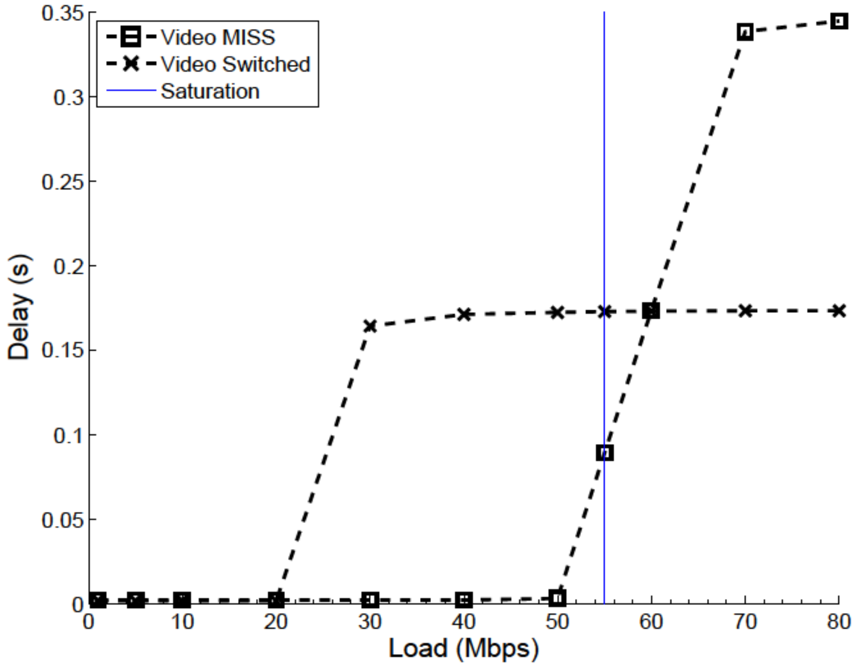


(a) Video Packets

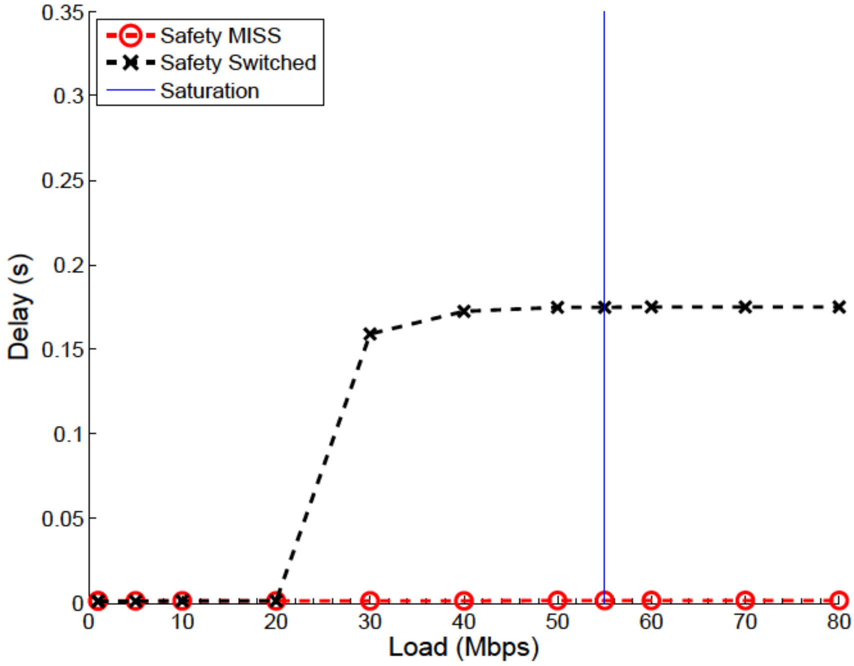


(b) Safety Packets

Figure 5.9: Packet Delivery Ratio of Video and Safety Packets



(a) Video Packets



(b) Safety Packets

Figure 5.10: Delay vs. Load Comparison for Video and Safety Packets

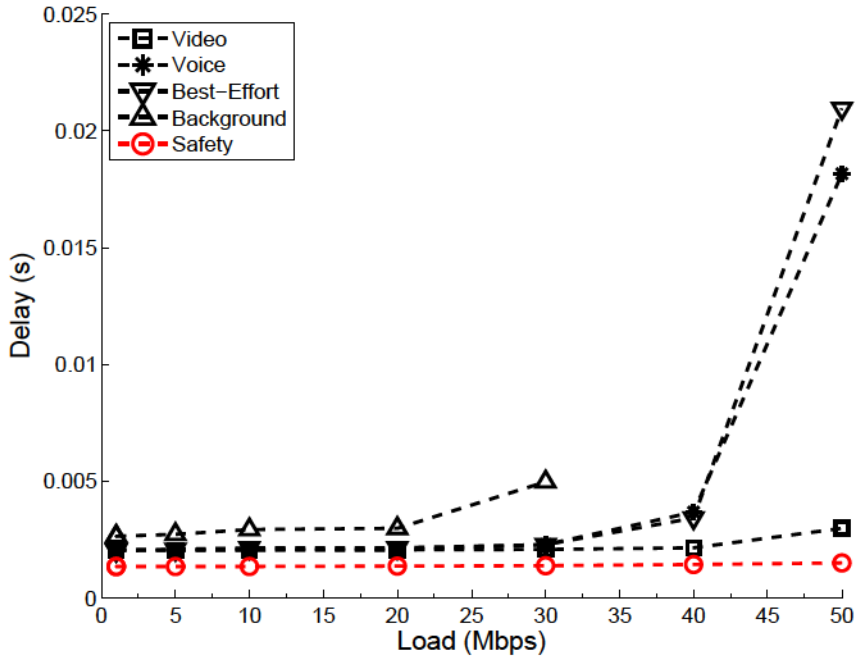


Figure 5.11: Delay Before Saturation vs. Load

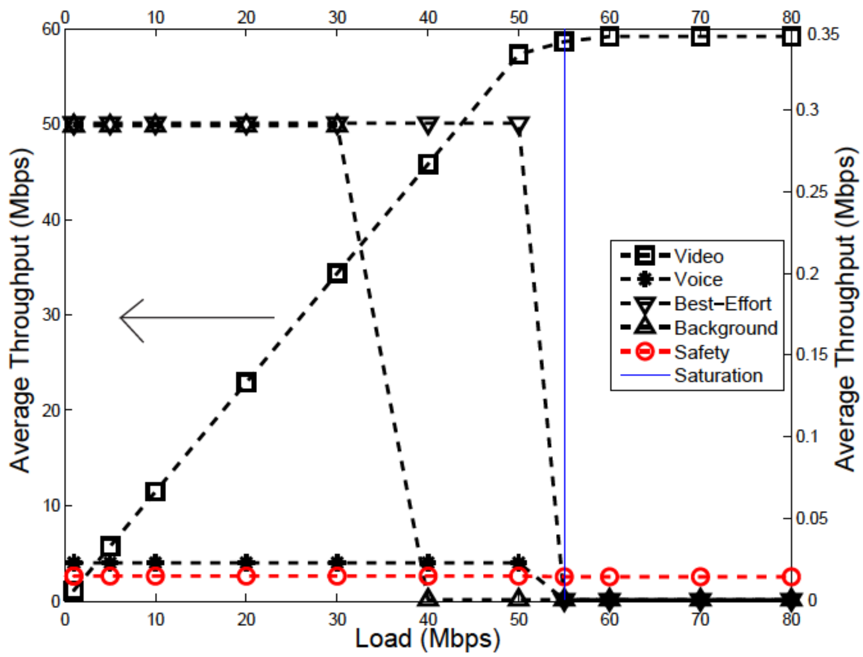


Figure 5.12: Throughput vs. Load

The background traffic is the last in terms of priority in the MISS. Up to 30 Mbps, there is none or little saturation in the environment and thus the packets get a chance of being transmitted. Above this threshold, which is influenced by the RAT with the highest capacity (RAT 3 with 27 Mbps), the packets with lower priority, such as the background ones, have a longer sejourn time in the queue and get eliminated.

In Figure 5.12, the throughput of the different traffic types is compared at different network loads. The left abscissa corresponds to the video plot, while the right abscissa corresponds to the other traffic services. It can be observed that the safety critical traffic type has a constant throughput rate, even after saturation, while for the other traffic types the throughput reduces as the load increases.

Video Evaluation

The scenario of automated driving in ITS where video is transmitted real-time from a vehicle to a control centre is assumed to be the target application in this section. Infotainment provision can also be considered, but in this case with downstream data to the vehicle. Number of papers have studied mechanisms supporting QoS in different types of networks but much less has been done to assess the quality achieved by a unified heterogeneous vehicular approach, where multiple RATs are used jointly in a vehicular environment. This work evaluates the difference in video quality, with the EvalVid framework, based on different parameters and profiles of the algorithm in the shim layer. The ability of performing Mean Opinion Score (MOS) calculation in real time [135] can be very useful for ITS. This section is also linked to the MISS implementation and OBU-ITS test bed, described in Chapter 6.

EvalVid

In the following set of experiments the 'Highway' sample, in YUV format[2], from the EvalVid video database [136] was chosen and encoded with MPEG-4. It is to be noted that any video can be assessed with the EvalVid framework but the 'Highway' video is the closest match to an ITS environment - a car driving down a highway.

[2]Refers to a family of colour spaces, similar to Red-Green-Blue(RGB) model

MPEG Decoder and Frame Types

The MPEG standard defines three types of frames: I, P, and B. *I frames* contain an entire image, which can be decoded independently. *P frames* are predicted frames which can only be completely decoded if the previous I or P frame is available. *B frames* can be decoded completely only if the previous and successive I or P frame is available. However, I frames contain the largest number of bits. Additional types of frames, e.g. slice *S* frames, which are less common, can be found in MPEG-4 but they are not used in this work as the assessed 'Highway' does not cotain any. For more details, please refer to the MPEG-4 standard[3] or the work of Richardson et al. [137]. The technical characteristics of the tested *Highway* video can be found in Table. 5.5.

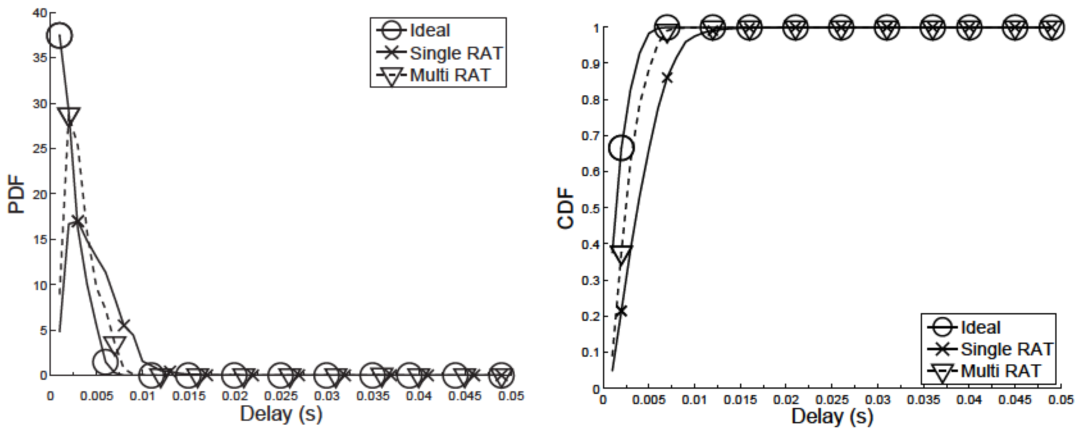
Table 5.5: EvalVid and Video Characteristics

Parameter	**Value**
EvalVid Version	2.7
Video	'Highway'
Encoding	MPEG-4
Encoder	ffmpeg (N-74587)
Frames	2000
I Frames	67 (161 packets)
P Frames	1933 (1933 packets)
B Frames	0
Average Packet Size	251 Bytes
I Frame Size	928 Bytes
P Frame Size	228 Bytes
B Frame Size	0

Video Delay and Prioritizing I Frames

In video transmission systems it is not only important to receive all the frames but also have frames that are displayed at a constant rate with a low variation of delay between frames. Package delay variation leads to jitter. These issues are generally addressed by buffers but the details of this technique goes beyond the scope of this thesis. In a heterogeneous approach where all the available links are used, the frames need to be sent in order to accommodate the estimated delay in the link and avoid excessive re-ordering at the receiver end. As described in Chapter 2, the EDPF algorithm artificially throttles transfer rates on faster paths with the aim of receiving packets in order. However, such an approach does not work correctly in a saturated environment as the delays are not under

[3] ISO/IEC 14496



(a) PDF (b) CDF

Figure 5.13: Video Frame End to End Delay

the control of the user and can vary highly. The algorithm approach chosen for the MISS system is different with the *'optimized video'* profile. If the video is of critical importance, such as in search and rescue situations or remote image processing for automated driving, but the available network capacity can not respond to the video bandwidth requirements, the MISS algorithm distinguishes between the different video frame types and places the most important frames (*'I'*) in the safety queue. The other frames remain placed in the designated video queue. The results are presented in Figure 5.14. The data rates under 30 Mbps (no saturation) are not plotted as they have a 100% delivery rate and a MOS close to ideal. The simulation was performed with a single RAT available (RAT ③ from Table 5.4). It can be observed that:

- when *I Frames* are tagged as safety packets, even if the received Number of Frames (NoF) decrease with an increasing load, the MOS is relatively constant.
- on the contrary when there is no differentiation between the video frames, the MOS degrades with the number of received frames.
- for 137 extra frames transmitted (6.85% of total frames) there is a quality improvement of 54% (1.4 compared to 2.77).
- the number of received frames is constant after a 80 Mbps load, as a result of the applied CoDel queue in the shim layer. The CoDel queue [114] eliminates the packets that have stayed too long in the queue waiting for transmission, thus reducing the queue time.

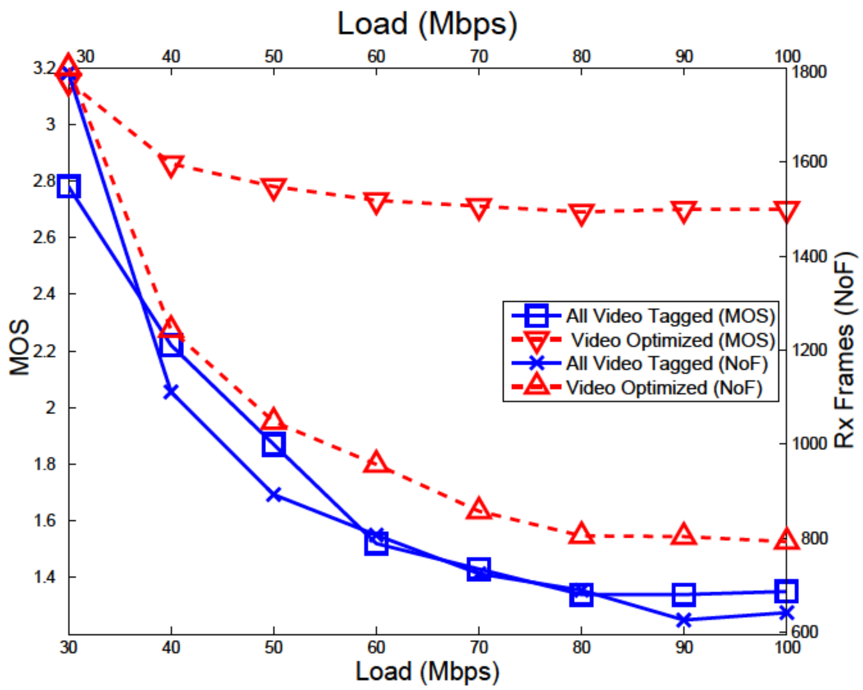


Figure 5.14: Comparison between MOS and Number of Received Frames with Video Optimization enabled

Non Saturated Environment

In the following section experiments have been carried out with the mobility scenario described previously (Figure 5.7(a)), with no saturation of the data link (data rate below the MR saturation threshold in Figure 5.8). The probability distribution function (PDF) (Figure 5.13(a)) and cumulative distribution function (CDF) (Figure 5.13(b)) of the end to end delay of the video frames show that the shim layer scheduling is beneficial even when there is only one RAT available compared to a switched scheme approach with only one RAT.Even if there is only one RAT with one transmission buffer, the shim layer can control and prioritize the access to the underlying buffer. The reduction of the frame end-to-end delay by the MISS algorithm can result in better real-time video quality by reducing the buffering at the receiver end. The PDF and CDF also show that when there are multiple RATs available the algorithm can send the packets on the link with the lowest delay and the performance approaches the optimum performance.

Another advantage is that the algorithm bases its decision on both delay and throughput, and can choose the RATs which respond best to the video requirements. If the algorithm chooses the RAT which has the highest throughput but

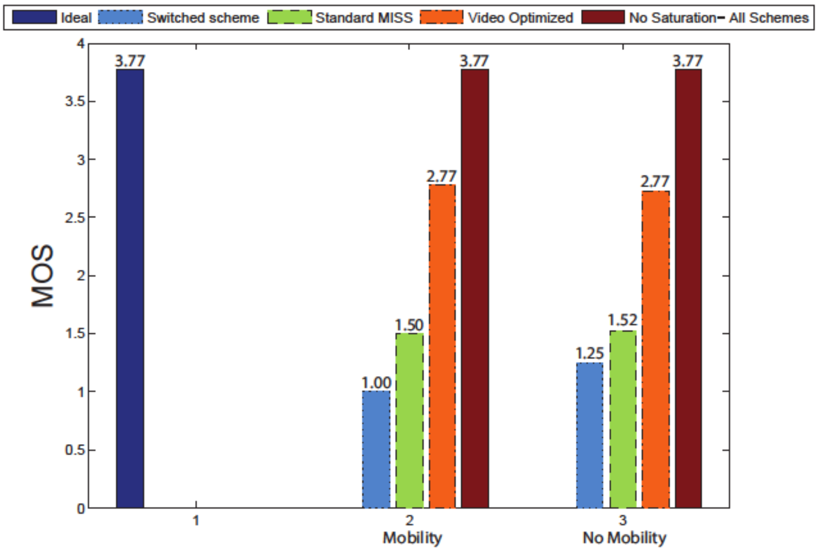


Figure 5.15: Summary of MOS Scores

ignores the link delay, frame jitter can occur and it is not suitable for a live video stream.

The performance clearly improves when multiple RATs are used and gets closer to an ideal performance. The ideal performance was calculated with no interference, saturation or delay, between the sender and receiver, similar to a direct point-to-point wired connection.

Saturated Environment

In the following scenario a saturated environment is defined as 10% above the combined total bandwidth. In a switched scheme, this value is 30 Mbps: maximum bandwidth is RAT 3 with 27 Mbps - Scenario 2 of Figure 5.16, while for this multi-RAT approach and scenario this value is 60 Mbps (Scenario 1 in Figure 5.16). The load is performed by increasing the video packets in the network. This approach is used to provide fairness for both single RAT and multi RAT schemes. When other type of traffic saturate the link, e.g. best-effort, due to the classification and prioritization of packets in the shim layer, the video packets always get priority and no variation occurs in the transmitted packets.

If a *'video optimized'* profile approach is tested in a mobile environment (Figure 5.7(a)) the difference of MOS between a standard MISS and a *'video optimized'* profile is of 1.28 (1.50 compared to 2.78 respectively) - set 2 in Figure 5.15. In the aforementioned figure, Set 3 represents a static environment, with

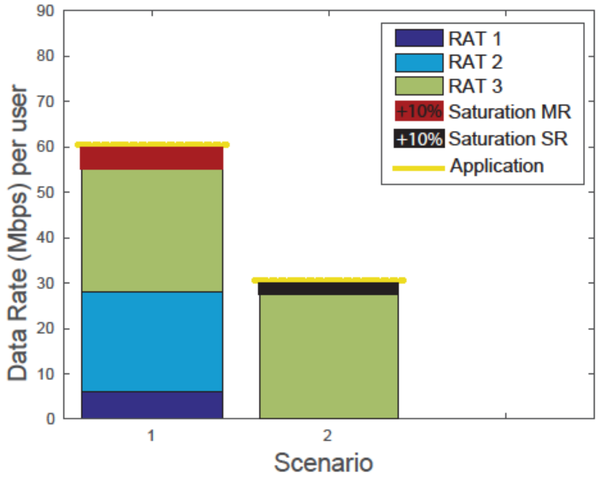


Figure 5.16: Definition of Multi-RAT and Single RAT saturation thresholds per user for the Prioritization of Video Messages experiments

only one RAT available. Both evaluated scenarios and all tested schemes perform ideally when no saturation is present in the link. It is to be observed that the MISS algorithm performs similarly in a mobile or a static environment, whereas in a classic switched scheme the performance degrades in a mobile environment. This is due to the numerous parameters taken into consideration for the decision making. It is also to be noted that all tested schemes reach an ideal score when no saturation is applied to the link.

Visual Comparison of Frames

Similar to Ke et al. [138], to illustrate how the difference in performance is perceived by an end user, the corresponding visual outputs of 5 frames are shown in Figure 5.17 with the help of YUV Player[4]. Each row represents one approach. The difference in position of the road sign is due to the previous lost packets. In the switched scheme, the road sign is essentially lost even though slight shadows are visible if observed closely. In the second row, when the MISS algorithm treats all video packets equally, there is substantial breakup in the image. When the *'video optimization'* profile is applied (3rd row), the quality is close to the ideal video results (4th row). In the *MISS Video optimized* case (3rd row), the images do break up slightly in between the I Frames but it is not noticeable in a selection of a small number of frames. The reason is the spacing between the

[4]`https://sourceforge.net/projects/raw-yuvplayer/` - [Accessed: 2016-02-15]

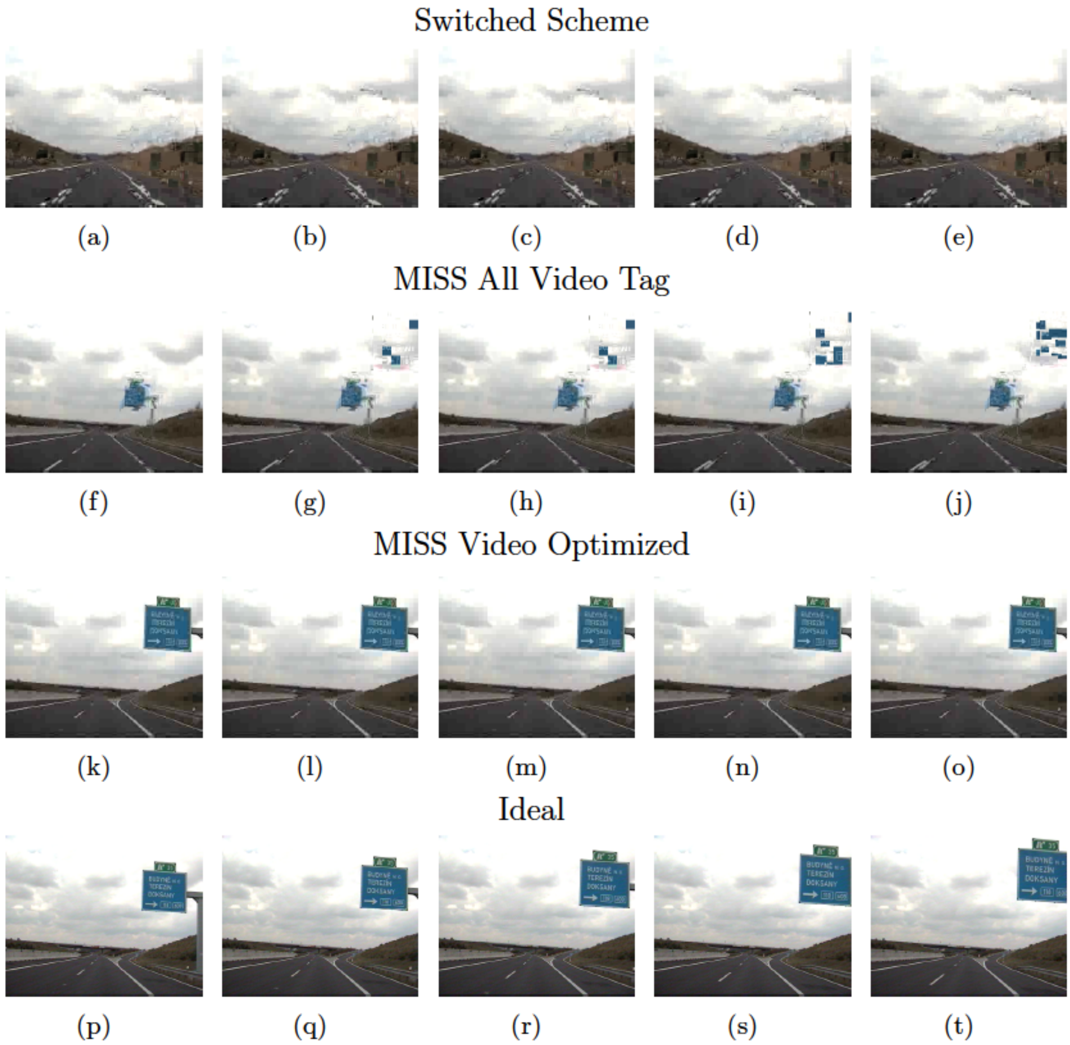


Figure 5.17: Visual Comparison of reconstructed 1049-1053 frames

I frames along with packet loss of the intermediate B frames which leads to the difference in MOS scores observed in Figure 5.15.

5.3.4 Multiple Queues - Multiple Users - Non-Cooperative Approach - Random Mobility

In this third set of experiments, a non-cooperative multiple users approach with different transmission schemes is studied. As described in Chapter 2, LTE can support up to 1200 active users in a rural environment with a delay under 55 ms [60]. However, by adding an increasing number of vehicles to the LTE network and in urban areas, the network can easily be overloaded. Offloading part of the

Table 5.6: Multiple Users ns-3 Simulation Setup

	Wi-Fi ①	**Wi-Fi ②**	**Wi-Fi ③**
RAT	802.11p	802.11n	802.11n
Frequency	5.9 GHz	2.4 GHz	5.18 GHz
Data Rate	6 Mbps	21.9 Mbps	27 Mbps
Link Delay	2.40 ms	1.73 ms	1.70 ms
APs	12	16	9
Propagation Loss Model	Two-ray	Log Distance	Log Distance
Transmission Range	125 m	50 m	50 m
AP Spacing	50 m	Safety Traffic	2 kbps
Transmit Power	20 dBm	Other Traffic	30 Mbps
Number of nodes	[10;50]	Transport Layer	UDP
Node speed	5 m/s	Network Layer	IPv6
Mobility	Random	Addressing	Static
Area	62,500 m^2	Receiver Sink	1
Queue Type	CoDel	Packet Size	1448 bytes
		Safety Packet Size	200 bytes
Simulator	ns-3.22	Simulation Time	100 s

users and/or the data appears as a solution in such a congested environment. The 802.11p with the DSRC network is a natural candidate as it is specifically designed for vehicular networks. However, work by Han et al. [86] shows that DSRC in conjunction with IEEE 802.11p exhibits poor performance in the event of a large number of vehicles. The goal of this simulation is to prove that the shim layer can work in a multi-user non-cooperative environment and to determine its performance in the event of a large number of vehicles.

Simulation Environment

The simulation setup is listed in Table 5.6. There are varying number of nodes, 10 to 50 with increments of 10 for each iteration, with a random mobility model in a 62,500 m^2 area. 20 nodes are depicted in red in Figure 5.18. With the specified ranges and the simulated environment any node has access to at least two 802.11p side units. Since 802.11p is not infrastructure based, the nodes can

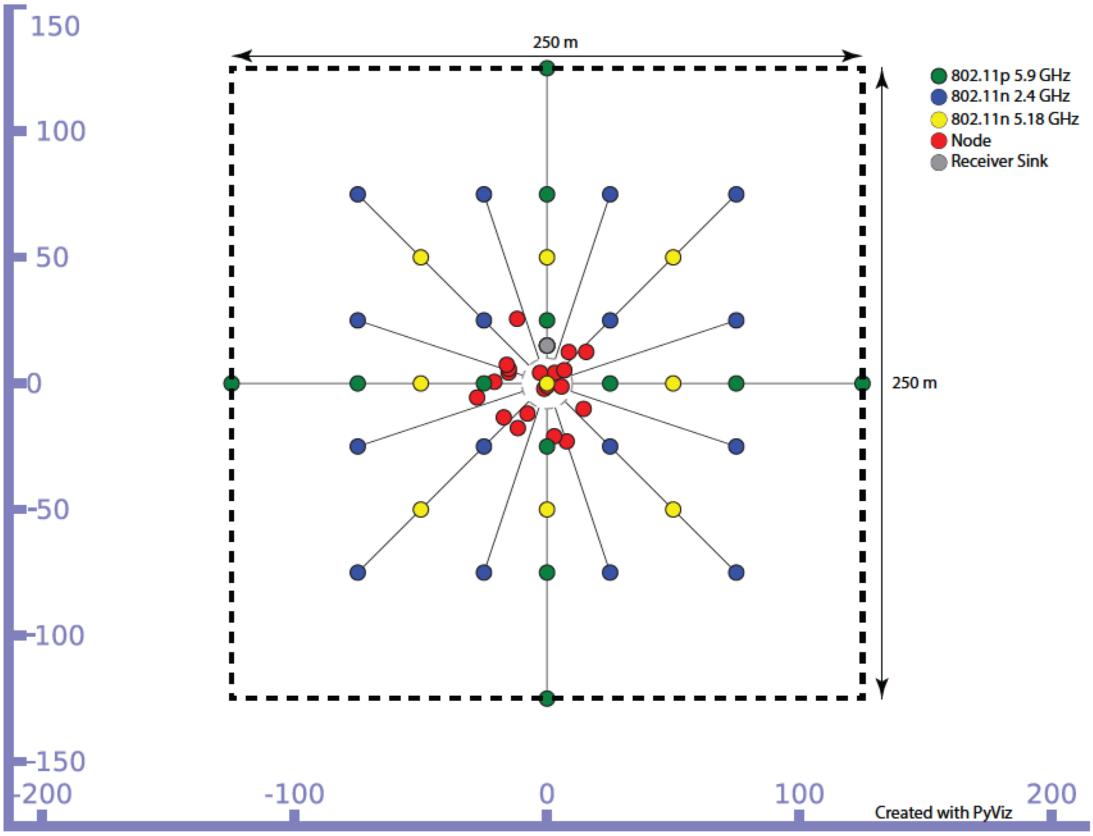


Figure 5.18: Multi node simulation

communicate ad-hoc between them. Signalling messages exchanged between the nodes can be observed in Figure 5.19. However, due to the setup of the simulation there are no safety messages exchanged directly between nodes as they all transmit information to the central control unit, also known as the receiver sink, seen in grey at coordinates (0,10) in Figure 5.18. All nodes act in a greedy manner and individually try to get as many packets through as possible. There is no cooperation between the users. All nodes are on the same channel and thus there is strong interference/collision.

The 'Log Distance Propagation Loss Model'[5] was used for the 802.11n 2.4 GHz and 5.18 GHz as the existing Wi-Fi APs are usually indoor. The log-distance propagation loss model is a radio propagation model that predicts the path loss a signal encounters inside a building or densely populated areas over distance. In addition, the maximum transmission ranges have been arbitrarily set to 50 m for the 2.4 GHz and 5.18 GHz. For the 802.11p, it is assumed that they are placed in open space, with 50 m spacing. Their applied model is thus 'Two-Ray Ground' propagation loss model. Their maximum transmission

[5]`https://www.nsnam.org/docs/models/html/propagation.html#logdistancepropagationlossmodel` - [Accessed: 2016-09-25]

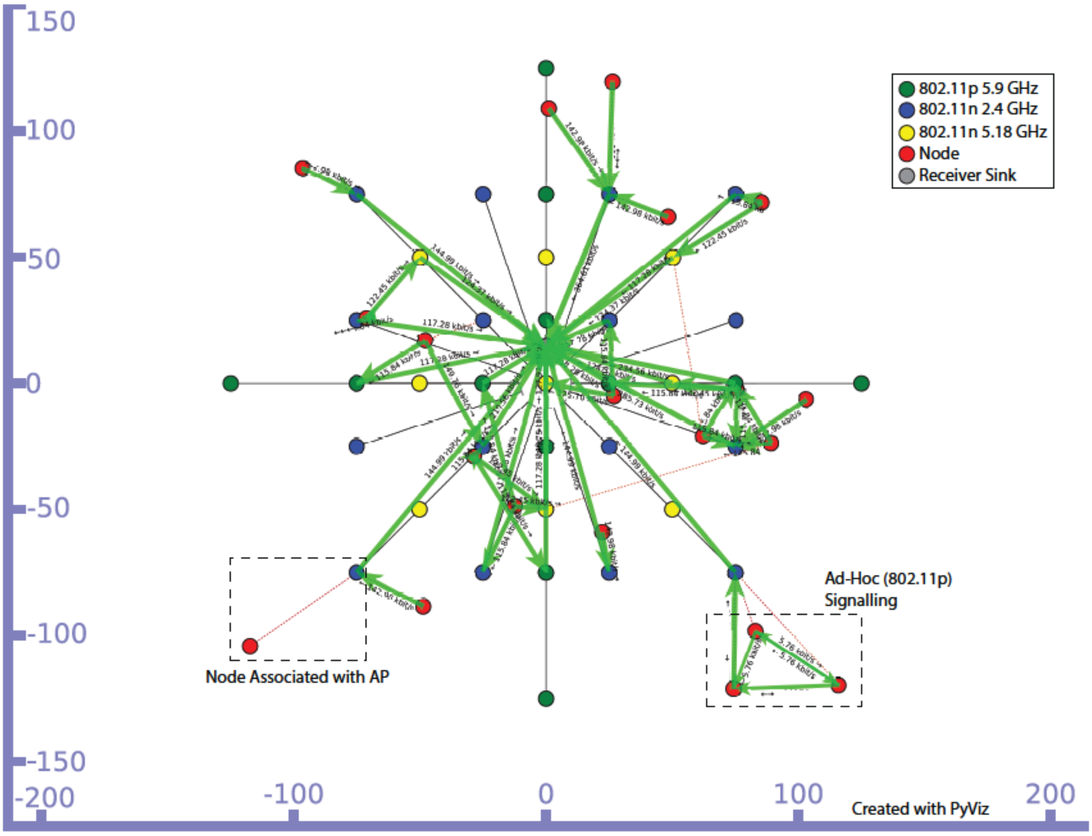


Figure 5.19: Nodes Connecting to different APs in ns-3 Simulation of Random Mobility Multi-User

range is 125 m. For this simulation the safety tagged messages are set similar to the Basic Safety Messages (BSMs). BSM is a 200-byte packet that is generally broadcast from every vehicle at a nominal rate of 10 Hz.

A saturated environment is defined as one where the data rate provided by the higher layers can not be responded by a single RAT. In this scenario, the highest data rate RAT is Wi-Fi 802.11n 5.18 GHz with 27 Mbps. The saturation threshold has been set to 30 Mbps as shown in Figure 5.20. Similar to the previous experiments, in the Switched case, all three RATs are accessed one at a time.

Results

The results are shown in Figure 5.21 and it can be observed that:

1. As the number of nodes increases, the shim layer PDR and delay performs similarly in both saturated and non-saturated environments, while

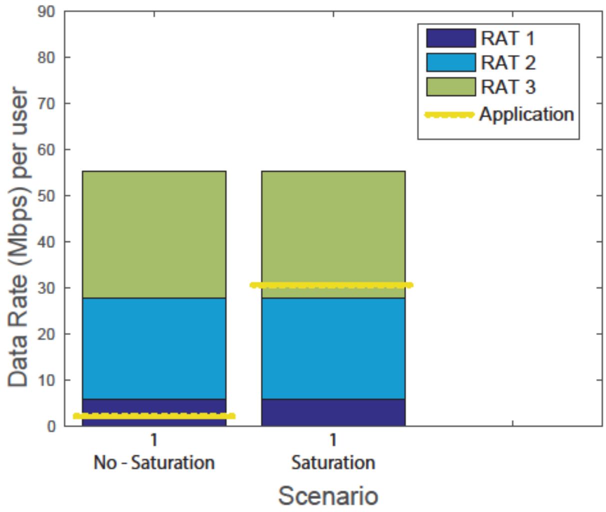
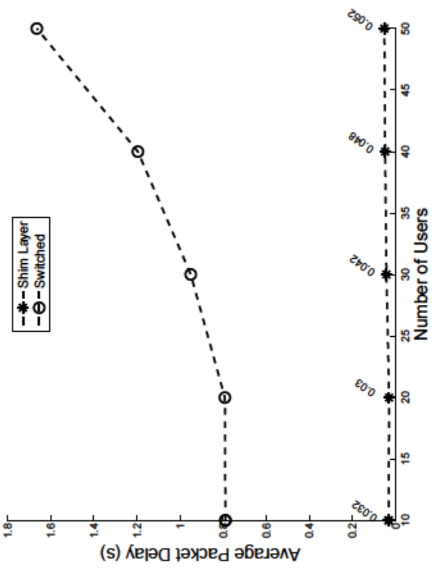


Figure 5.20: Saturated and Non-Saturated Data rate scenario description and capacity per RAT per user for non-cooperative multi-user simulations

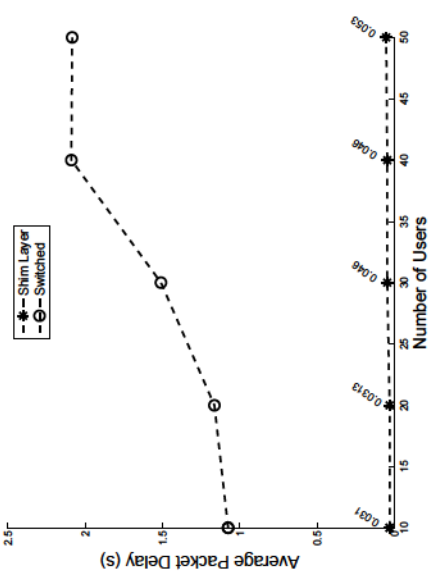
the switched scheme has lower performance as the number of nodes increase. This is a normal situation with Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as the number of collisions increases with the number of users. The high number of users increases the back-off time which in return increases the delay of the packets. As this is expected for Wi-Fi 802.11n 2.4 GHz and 5.18 GHz, 802.11p should work with a large number of numbers. It confirms the work by Han et al. [86] showing that IEEE 802.11p exhibits lower performance in the event of a large number of vehicles.

2. Certain safety values have higher delays due to the random movement of the vehicles - this influences the density in certain central areas, as can be seen in Figure 5.18.

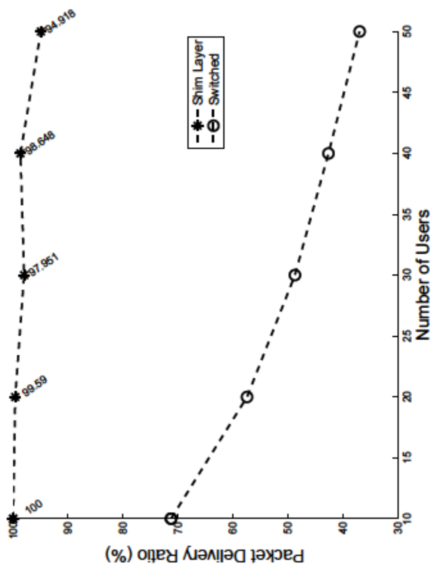
3. There is a drop in the PDR with an increase of number of users, even with the shim layer. This is related to the fact that the safety messages are not broadcasting to all the 802.11p APs, but only to the closest one to the node.



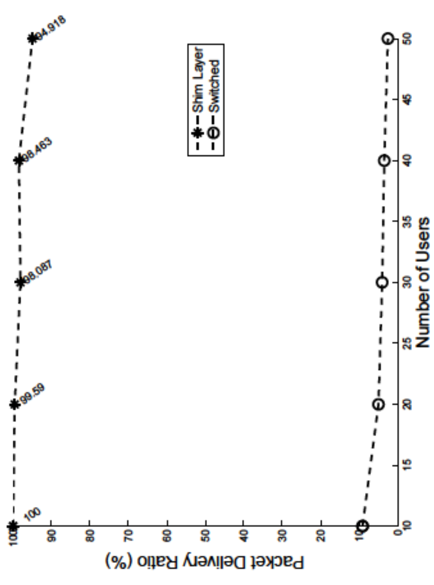
(a) Safety Messages Average Delay in a Non-Saturated Environment



(b) Safety Messages Average Delay in a Saturated Environment



(c) Safety Messages Packet Delivery Ratio in a Non-Saturated Environment



(d) Safety Messages Packet Delivery Ratio in a Saturated Environment

Figure 5.21: Multi User Non-Cooperative Simulation Results

5.4 Summary

The shim layer scheduling algorithm has been tested with regards to different transmission schemes and data rate scenarios. It is transparent for the different Radio Access Technologies and it can increase the amount of data successfully transmitted from a user perspective. The results also show that safety critical traffic can be prioritized in terms of throughput and delay. The scoring model provides more flexibility for delay sensitive applications, can accommodate different performance metrics, adapt its decision based on user-specified profiles and can be adjusted to satisfy the broad requirements of ITS. Video traffic and quality of experience is also greatly improved with the video optimized profile. The shim layer can be beneficial in a non-cooperative multi-user environment, with a high number of users but the underlying RATs limitations are also limiting the shim layer performance as the number of users increase.

Chapter 6

MISS Implementation

"Knowing is not enough; we must apply. Willing is not enough; we must do."

[Johann Wolfgang von Goethe]

6.1 Introduction

In this chapter, the shim layer implementation is defined in two steps: the first step is the usage of real world data to evaluate the advantages of the shim layer with three mobility types (walking, cycling, driving) and the influence the same mobility types have in heterogeneous wireless networks (Section 6.2). Realistic simulations are performed by generating mobility traces of Oxford from Google Maps and overlaying the real locations of existing Wi-Fi Access Points. The second step is the evaluation and implementation of the scheduling algorithm on hardware (Section 6.4.2) in the Oxford Brookes University - Intelligent Transport System (OBU-ITS) project, described in Section 6.3. The objective is to show that the shim layer can work on hardware in real-world situations with existing standards. The experiments are expected to provide a validation for part of the single user simulation results previously carried out.

6.2 Real World Data and Study of Mobility Cases

The objectives of the real-world data simulation performed in this section are:

1. To show that if the shim layer is implemented on hardware, all users can have a benefit of using the approach, regardless of the mobility type (walking, cycling, driving).
2. To show what mobility type (walking, cycling and driving) is the most cost efficient way, from a wireless communication perspective, of travelling within a dense urban environment.
3. If Wi-Fi is assumed to be the most cost-effective RAT, to assess how much of the data can be offloaded from cellular to Wi-Fi.
4. To show that the shim layer can respond to different users profiles in ITS within a real-world environment.

Simulation Environment

Three different transport methods are compared: driving, cycling and walking. The simulated Oxford city center part can be observed in Figure 6.1. The full interactive map is available to view online[1]. Two scenarios are tested:

1. The nodes are travelling between Oxford Train Station (Ⓐ) and Oxford Brookes University Headington Campus (Ⓓ). This scenario involves different routes for the 'walking' and 'cycling'-'driving' nodes due to the traffic restrictions in Oxford City Center.
2. 'High Street Scenario': The nodes are travelling from 141 High Street (Ⓑ) to Cowley Place (Ⓒ). This area is characterized by a high number of available APs. All nodes follow the same route.

It is assumed no authentication is required and a static IP address scheme is used. This is necessary to allow the shim layer to have only a single IP address. It is also assumed a full cellular link coverage was available and that all packets that could not be sent over Wi-Fi are sent over cellular.

[1] `http://tinyurl.com/obu-npa-eduroam-ox` - [Accessed: 2016-08-17]

Table 6.1: Oxford Eduroam Mobility NS-3 Simulation Parameters

	Wi-Fi ① 🔴		
RAT	802.11n		
Frequency	2.4 GHz		
Data Rate	5.5 Mbps		
Link Delay	Various		
APs	162		
Propagation Loss Model	Two-ray		
Transmission Range	25 m		
Queue Type	CoDel	Data Traffic	128 kbps
Transmit Power	20 dBm	Packet Size	1448 bytes
Number of nodes	1	Transport Layer	UDP
Node speed	Various	Network Layer	IPv6
Mobility	Various	Addressing	Static
Coverage	Various	Receiver Sink	1
Simulator	ns-3.22	Walking	3121 s
Cycling	1181 s	Driving	849 s

The full simulation parameters can be observed in Table 6.1. For the purpose of testing, the available AP bandwidth for a single user is limited to 5.5 Mbps, even though the maximum available throughput for one AP is 27.1 Mbps. This aims to recreate the bandwidth limitations generally placed on public Wi-Fi APs to avoid a single user using all the available bandwidth. The node sends a constant data traffic of 128 kbps over the entire simulation. 128 kbps corresponds to an online radio stream and is assumed to be a good example of constant connection data rate. No safety traffic is being sent as the main objective of this experiment is to show the benefit of the shim layer in relation to different mobility types and how much data can be offloaded to Wi-Fi. As in previous experiments, the packet payload size of 1448 bytes was chosen to avoid fragmentation at the IP layer (1500 bytes MTU - 52 bytes IP header). The two-ray propagation loss model was chosen as it was assumed the node would have line of sight to the AP. The attenuation from the walls has not been considered but the range of the AP has been limited in order to avoid large areas covered by a single AP in an attempt to take into account the attenuation from the surrounding buildings. The transmission range of each AP is set to an arbitrary value of 25 meters. The

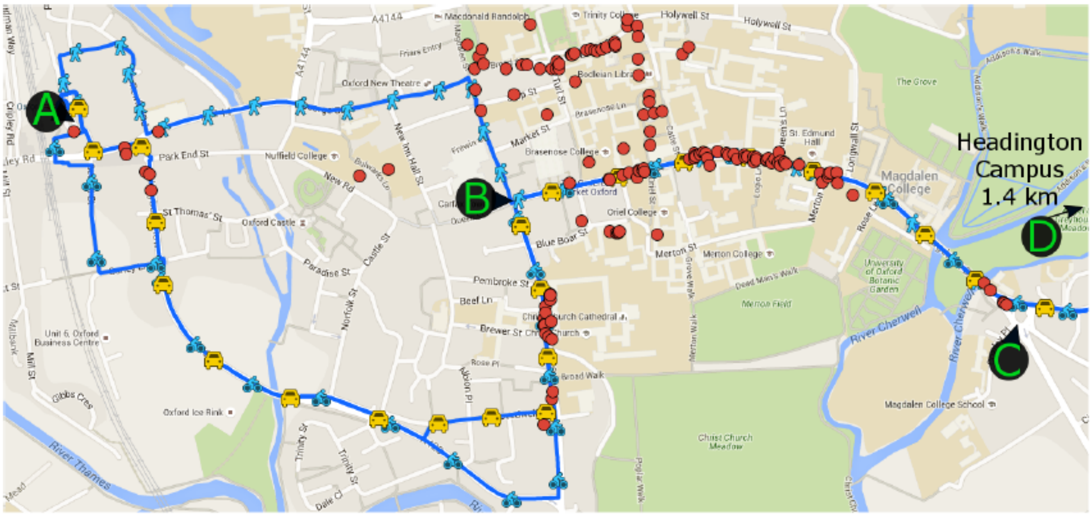


Figure 6.1: Google Maps Mobility Caption of Oxford City Center overlaid with Eduroam AP locations (Map data: Google)

number of APs and their location is related to the real-world database of APs, further described in Section 6.2. The simulation time associated with each of the transport modes are related to the travel time between Oxford Train Station (Ⓐ) and Oxford Brookes University Headington Campus (Ⓓ).

Real-World Data

The Routes Mobility Model package [139] was used to integrate the Google Maps mobility and directions in ns-3. The simulated nodes (one per simulation) try to maintain real-world speeds for the type of road they are travelling: decelerating for a curve, a roundabout, an intersection, and accelerating after those obstacles are overcome.

The Eduroam[2] (education roaming) APs were chosen to be used as potential usage for ITS as they are omnipresent in the center of Oxford due to the numerous University of Oxford buildings. Eduroam is the secure, world-wide roaming access service developed for the international research and education community. It allows students, researchers and staff from participating institutions to obtain Internet connectivity across campus and when visiting other participating institutions.

[2]Eduroam: education roaming, `https://www.eduroam.org/` - [Accessed: 2016-04-08]

Table 6.2: WiGLE Database Results

Parameter	**Value**	**Total APs**	**1606**
Latitude 1	51.738	QI > 0	985
Longitude 1	-1.3066	QI > 1	934
Latitude 2	51.7651	QI > 2	545
Longitude 2	-1.1941	QI > 3	498
Date Range	[01/01/2015 -	QI > 4	288
	06/04/2016]	QI > 5	236
SSID	eduroam	QI > 6	162

The Eduroam APs locations were extracted from the WiGLE[3] database. WiGLE is a crowd-source website for collecting information about Wi-Fi APs. The selected area is between GPS coordinates 51.738, -1.3066 and 51.7651, -1.1941, which corresponds roughly to the area of Oxford inside the ring road. The results can be seen in Table 6.2. The Quality Indicator (QI) parameter is an arbitrary WiGLE metric[4] for an observed point: if an AP is seen on more than one day, or by more than one user, the value increases as it is more likely to be stable. If the AP is seen only once by one user, the QI is set to 0. The QI value increases with the number of views by different users and the maximum value is 7. In the represented table, we indicate how many APs were found with a QI larger than a specific value. For example, there are 1606 APs with a QI of 0 or higher, and 985 with a QI strictly superior to 0. This includes all the APs with a QI equal to 1 up to 7. For the simulation only the APs with the highest QI, strictly superior to 6 (e.g. QI = 7 since 7 is the maximum value), were chosen, resulting in 162 APs. From the total number of APs (1606), 1594 are 2.4 GHz APs and twelve are 5.2 GHz APs. For simplification, the 802.11n 5.2 GHz APs have been considered as 2.4 GHz for the purpose of the simulation.

Results and discussion

In Figure 6.2, the percentage of data and the number of packets sent over Wi-Fi for the different mobility types (walking, cycling, driving) is presented. It is to

[3]WiGLE:Wireless Network Mapping, `https://wigle.net/` - [Accessed: 2016-04-08]

[4]The original WiGle metric is named 'QoS' but it is only based on the number of times a user reports the Access Point. To avoid confusion with the network Quality of Service, the WiGLE metric was renamed Quality Indicator (QI).

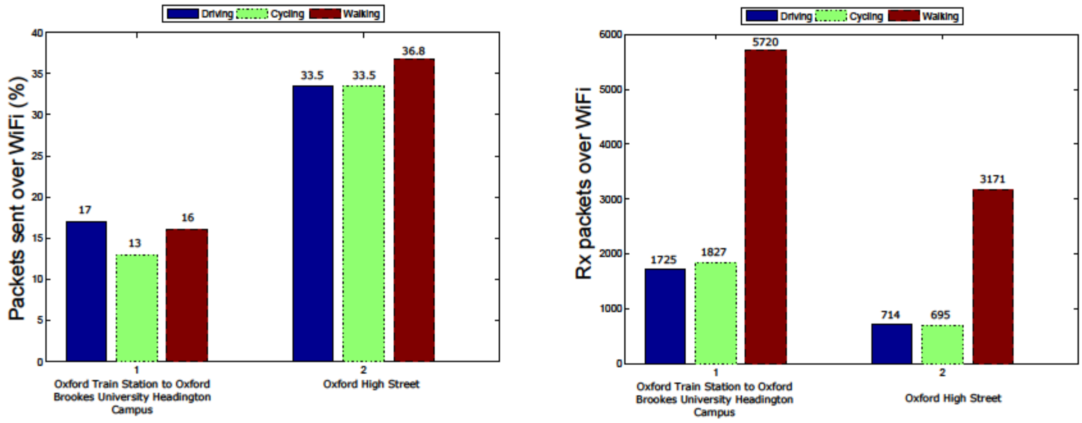


Figure 6.2: Percentage of data and number of sent packets over Wi-Fi

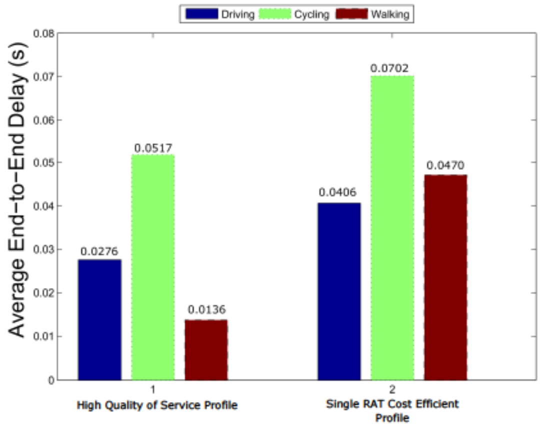


Figure 6.3: Comparison of End-to-End Delay for Wi-Fi only profile vs. High QoS profile

be noted that in the first scenario, driving has a higher percentage than cycling and walking due to the speed of the node, but also the route - the nodes respect traffic rules and take the shortest path for their mobility type. The route is also the reason why the walking node does not have a higher percentage of data sent over Wi-Fi in the first scenario compared to the driving and cycling. In the 'High Street Scenario', where all nodes follow the same route, the walking node has a higher percentage of transmitted data than both cycling and driving: 36.8% vs 33.5%. It can also be observed that a walking node is capable of sending 3 times more data over Wi-Fi, 5870 packets against 1827 packets, than the other means of transport in the first scenario, and 4 times in the second scenario - 3171 packets against 714 packets (Figure 6.2). This is related to the time each node spends in the area of an AP.

To further evaluate the functioning of the shim layer, the delay values of two different profiles were compared in the 'High Street Scenario' (Figure 6.3). The

’High Quality of Service Profile’ uses parallel transmission and uses both links to transmit a packet. The ’Single RAT Cost Efficient Profile’ uses only Wi-Fi, when available, to transmit the packets. It can be observed that the ’High Quality of Service Profile’ has an average end-to-end delay 0.02 s lower than a ’Single RAT Cost Efficient Profile’. The highest end-to-end delay is observed for the ’cycling node’. This can be explained by the constant speed of the ’cycling node’ and the resulting handovers. Even if the vehicle ’driving node’ speed average is higher than the cycling, the variations are larger. The car node speed is influenced by intersections, traffic lights and curves while the bicycle node has a more constant speed, even if advancing at lower speeds.

6.3 The Oxford Brookes Intelligent Transport Systems Test Bed

The OBU-ITS platform, as described in [140], is an electric powered autonomous off-road all-terrain vehicle based on a full-size quadbike (Figure 6.4). The vehicle is intended to be like a ’pack mule’ that has its own sense of situational awareness around groups of people, and can follow simple commands such as ’follow me’, ’park over there’, and ’unload yourself from the van’. Rather than implementing expensive, computational intensive algorithms on each of the vehicles, a central server can process all the information captured by the sensors and the commands are to be sent back to the car. Cloud computing with remote image processing can be a solution. The vehicles can thus be controlled as a fleet. The vehicle can still make decisions based only on its sensors but gathering and having information from multiple surrounding sources helps in the decision making process and enhances transportation safety and efficiency. Partially automated vehicles could be used in more controlled environments, such as hospitals or airports and have less intelligent autonomous capabilities in order to reduce cost and have a faster implementation on a large scale.

A variety of projects are contributing to the design and construction of this vehicle/system: *Intelligent motor control for electric vehicles*, *Road scene understanding*, *Visual guidance and navigation* and *Heterogeneous Wireless Networks*.

The contribution of this project to the ITS programme is to investigate the use of *Heterogeneous Wireless Networks*. The objective is to demonstrate that heterogeneous networks can improve the performance of the communication in a vehicular network. The communication system uses heterogeneous wireless

Figure 6.4: The Brookes Intelligent Transport System Off-road all-terrain test vehicle

access technology to accommodate different coverage areas. The objectives are both to reduce delay and increase the quality of the streamed video images in order for the computer vision algorithm to have the best images possible.

6.3.1 Test Vehicles

Two vehicles are part of this project: a quad-bike and a small rover, each described below.

Quadbike

Originally, the quad-bike was petrol powered. The petrol engine has been replaced with a battery powered electric engine. Additionally, cameras were mounted at the front, as well as a computer. The box at the back of the quad-bike also contains a 802.11n 2.4 GHz AP to have a wireless interface with the controller. If reference is made to the J3016 SAE International Standard on levels of automated driving [141], the level of automation of the quad-bike is between level 2 and 3. Level 2 is a partial automation state where the system is only in charge of the execution of steering and acceleration/deceleration. In Level 3, the system (vehicle) is also responsible for the monitoring of the driving environment - also named as 'Conditional Automation'.

Figure 6.5: The Brookes 'Rover' vehicle

Rover

For development purposes, a miniature version of the quad-bike has also been developed, named the 'Brookes Rover' (Figure 6.5). The 'Brookes Rover' vehicle reproduces the main features of quad bike: camera, communication interface and central control unit. It is mainly used for indoor testing. It is equipped with a Raspberry Pi and camera for video streaming, Arduino boards for the ultrasonic sensors and a 802.11n 2.4 GHz wireless AP for the communication interface. The ultrasonic sensors are used as a backup solution in case the computer vision algorithms fail to identify an obstacle.

6.3.2 Tested Wireless Technologies

In order to test the heterogeneous aspect and the benefits of the shim layer, the quad-bike can be equipped, for the duration of the tests, with different radio access technologies. The is done through the intermediary of a laptop placed on the quad-bike for the 802.11n RATs and through a USRP box for the 802.11p RAT. The detail of the wireless equipment used is listed below and the hardware can be seen in Figure 6.6:

1. **Wi-Fi 802.11p** - The work made available by Bloessl et al. [142] is used to have a full 802.11p SDR based 802.11 Transceiver using GNU Radio.

2. **3G/LTE** - One dongle is used for each technology 3G/4G(LTE).

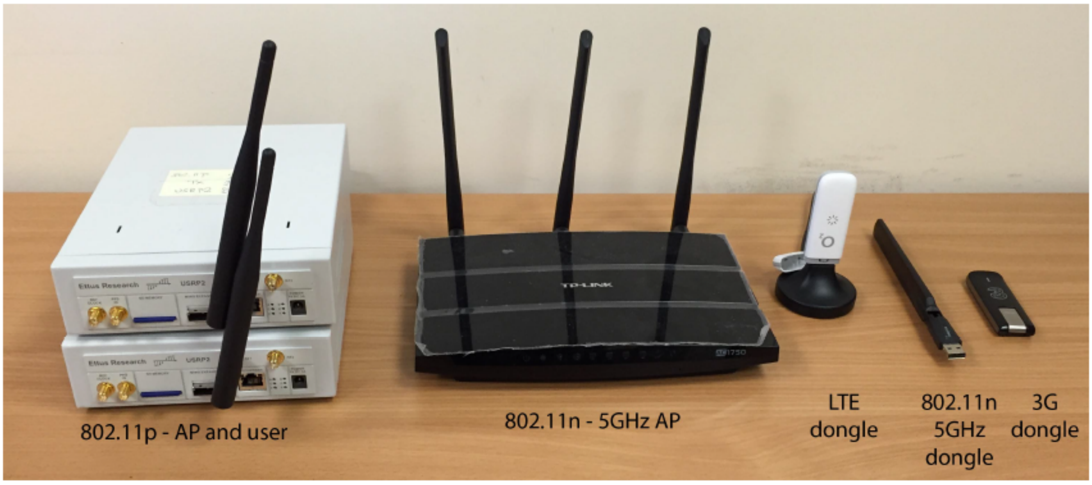


Figure 6.6: Wireless Hardware and Interfaces Used for the OBU-ITS testing

3. **Wi-Fi 802.11n** - The internal network card of the ITS laptop is used (Broadband BCM43224) for the 802.11n 2.4 GHz. The 802.11n in the 5 GHz band is tested with an external antenna (EW-7811UAC).

All the interfaces are connected to a laptop (MacBook Pro Late 2009, Linux Ubuntu 14.04 LTS), placed on the quad-bike. Smaller devices were considered, such as RPi, but currently they can not respond to the processing power requirements of the algorithm. Vehicles can provide more resources than other types of mobile networks such as large batteries, antennas, and processing power. Therefore, conserving such resources in vehicular networks is not a major concern and it is assumed there is no constraint on the energy consumption. The GNU Radio [143] is interfaced with ns-3 through a TAP device, which creates a virtual kernel device. The TAP device acts an intermediary between the IP layer of the operating system and the MAC layer of the connected network device. It can be considered similar to a FIFO queue where the first packets that are sent to the TAP device, are being read and processed by the network device.

NS-3 Emulation Mode

In ns-3 emulation mode the network devices appear similar to a ns-3 simulated device from the upper layers, but the upper layers (IP and upward) are linked to a real physical network using a TAP interface. The conceptual model of the common layers from the IP Layer upwards along with the Shim Layer's interaction with the emulated layers is presented in Figure 6.7. The data is uploaded via all interfaces and received only via Wi-Fi.

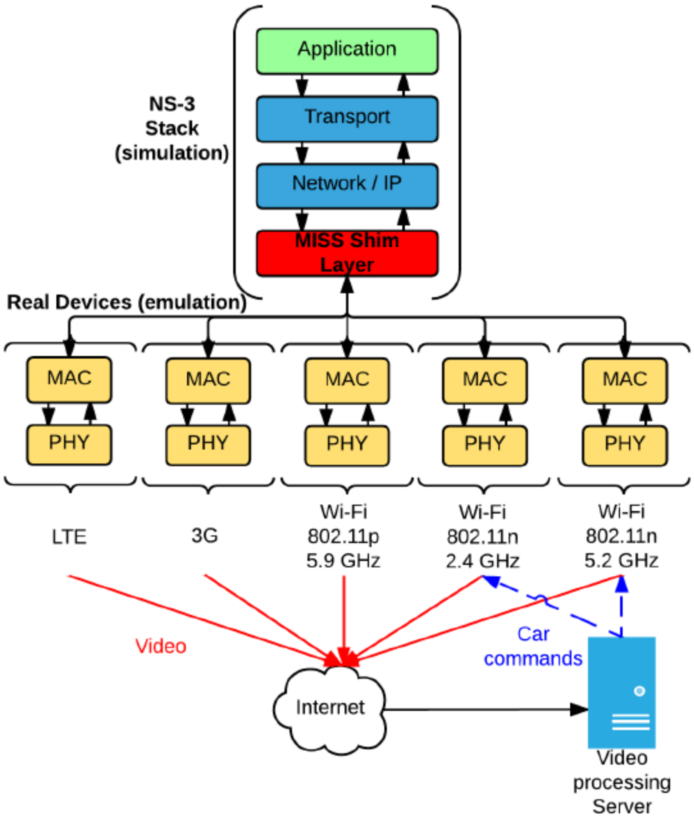


Figure 6.7: Conceptual model of the emulated shim layer

The default time scheduler behaviour in ns-3 is non real-time. Between two events the simulation advances the simulation time to the next scheduled event regardless of the real time difference between the events. Similarly during an event execution, simulation time is frozen. With the real time scheduler, the behaviour is similar during execution time (i.e. simulation time is frozen), but between events, the simulator will attempt to keep the simulation clock aligned with the machine clock[5]. The real time scheduler is needed for the emulation approach and for the algorithm implementation in the test bed.

6.3.3 Test Environment: Wheatley Campus

A functional Wi-Fi wireless connection from a PC to the individual vehicles has been produced. The extended service set around the Ⓡ building provided a suitable testing environment for a multi-channel Wi-Fi wireless connection system to the quad bike and/or the rover.

[5]`https://www.nsnam.org/docs/release/3.23/manual/html/realtime.html` - [Accessed: 2016-04-22]

Figure 6.8: Map of Testing Environment on Wheatley Campus

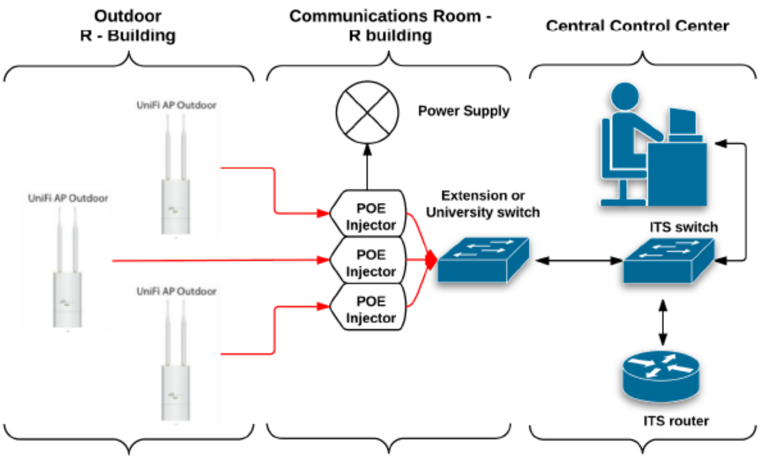


Figure 6.9: 802.11n 2.4 GHz AP wiring diagram

The test environment can be seen in Figure 6.8 as well as the received signal strength on the roads and fields accessible by the quad bike around the campus. The received signal strength measurements have been performed using Wi-Fi Explorer on a sunny, windy day (ambient temperature 2° C). The receiver, a laptop with AirPort Extreme firmware version Broadcom BCM43xx 1.0 was always oriented towards the closest line of sight access point. Three 802.11n 2.4 GHz AP are available, placed around the Ⓡ building. The backbone can be seen in Figure 6.9.

The Ⓣ area in Figure 6.8 is the heterogeneous test environment where RATs other than the 802.11n 2.4 GHz have been used (Figure 6.10). These tests are described in Section 6.4.2.

Figure 6.10: Map of Heterogeneous Testing Environment on Wheatley Campus

6.4 Hardware Implementation of the Shim Layer

The hardware implementation of the shim layer is divided in two subsections: the first with an initial testing via a single RAT for remote image processing in Section 6.4.1 and the second with the full heterogeneous and scheduling algorithm hardware implementation in Section 6.4.2.

The first tests were used to set the foundations for the full hardware results and to experiment if remote image processing for automated vehicles can be achieved with a single RAT. The second phase involved implementing multiple RATs on hardware and testing the shim layer implementation.

6.4.1 Initial Tests: Obstacle Avoidance

Most computer vision algorithms do not work with high resolution images in real-time as it is a challenging requirement, especially for mobile and embedded computing architectures [144]. Often, it is possible to trade off quality for speed. A resolution image of 640x480 or higher, with 30 frames per second, is necessary for fine-grained boundaries. If such a resolution is assumed, a required 27.6 Mbps data rate is required. For a 1024x768 resolution, 141.25 Mbps is needed. Heterogeneous systems become thus a necessity as none of the current wireless technologies can provide such data rates in non-ideal environments. Additionally, in vehicular networks, the links tend to be far less predictable than in a more static environment. This characteristic prompts the development of opportunistic higher layers that should take advantage of a good link while it lasts without counting on its longevity.

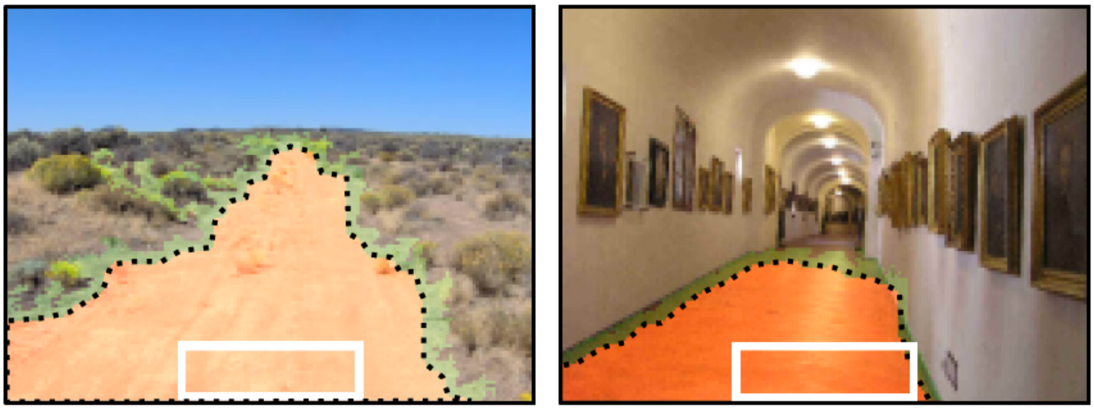


Figure 6.11: Examples of image segmentation into traversable and non-traversable regions in both outdoor and indoor environments [145]

Methodology, Testing Environment and Results

In order to demonstrate the capability of remote image processing for the OBU-ITS robotic platform, Sapienza et al.'s [145] computer vision algorithm was used which automatically guides the robot away from oncoming obstacles. A camera was placed at the front of the OBU-ITS platform and images were then transmitted to a server. The vision algorithm takes as input an RGB image and outputs a speed and steering angle to re-direct the autonomous platform. After performing semi-supervised image segmentation into traversable and non-traversable regions (Figure 6.11), the vision algorithm estimates the distance to the nearest obstacles using trigonometric identities. Finally the distance estimates are analysed and the largest obstacle free areas beyond a predefined distance are identified as possible movement directions [145]. The code for the real-time autonomous guidance algorithm is available online[6].

Initial tests have been performed on the isolated field, marked with a Ⓣ on Figure 6.8 with the quad bike speed limited at 5 km/h, for health and safety considerations. The testing parameters can be see in Table 6.3. The lowest

[6] `https://sites.google.com/site/mikesapi/downloads` - Accessed: 2016-08-12

Table 6.3: Obstacle Avoidance Environment Setup

	Wi-Fi ① ●		
RAT	802.11n		
Frequency	2.4 GHz		
Data Rate	Various		
Link Delay	Various		
APs	3		
Propagation Loss Model	Real-World		
Transmission Range	>50 m		
Queue Type	FIFO	Video Size	160x120
Shim Layer	No	Frames / s	15
Number of vehicles	1	Transport Layer	UDP
Vehicle speed	5 km/h	Network Layer	IPv4
Mobility	Random	Addressing	Static
Coverage	Various	Receiver	1
Tools	OpenCV, Hardware, RPi Wireshark, Gstreamer	Testing Time	Various

low video size and frames per second (fps) the vision algorithm can function correctly has been chosen, 160x120 and 15 fps. The three APs around the Ⓡ building, marked with pink pins on Figure 6.8, have been used. The standard Linux FIFO queue with IPv4 and UDP have been selected as the shim layer was not implemented in these experiments.

The quad bike avoided the cone obstacles successfully[7]. On a single thread the computer vision algorithm took approximately 5 ms to run on a single image of size 160x120. In the scenario with a single Wi-Fi interface and no optimization of the standard Wi-Fi algorithms, the round trip for the control message to reach the quad bike was around 400 ms, with values up to 800 ms. The value needs to be considerably lower for an efficient obstacle avoidance detection at higher speeds. Improvement could be achieved on the encoding and compression of the video on the transmitter side as well as the optimization of the network. To reach lower values required for a more efficient obstacle avoidance detection, implementing a heterogeneous wireless system on hardware could be the solution.

[7]For a visual representation the reader is invited to see the available online project video - `http://tinyurl.com/its-brookes` - [Accessed: 2016-08-12].

Table 6.4: Hardware Implementation Testing Setup

	Wi-Fi ① (green)	**Wi-Fi ②** (blue)	**Wi-Fi ③** (yellow)
RAT	802.11p	802.11n	802.11n
Frequency	5.9 GHz	2.4 GHz	5.2 GHz
Manufacturer	Ettus	Linksys	TP-Link
Model	USRP N210	WRT160N	AC1750
Data Rate	20 kbps	19.5 Mbps	58 Mbps
Channel	178	Auto	Auto
Tx Gain	25 dB	Auto	Auto
Antenna Height	1.5 m	1.5 m	1.5 m
Vehicle Antenna	1 m	1 m	1 m
Link Delay	Various	Various	Various
APs	1	1	1
Propagation Loss Model	Real-World	Real-World	Real-World
Transmission Range	Various	Various	Various

AP Spacing	10 m	Safety Traffic	20 kbps
Security	None	Other Traffic	Various
Number of nodes (red)	1	Transport Layer	UDP
Node speed	$\approx$ 11 km/h	Network Layer	IPv6
Mobility	Circuit	Addressing	Static
Area	$\approx$ 8,780 m^2	Receiver Sink (grey)	1
Perimeter	438 m	Packet Size	1448 bytes
Queue Type	CoDel	Safety Packet Size	200 bytes
Tools	ns-3.22, USRP GPS, Hardware Wireshark	Testing Time	$\approx$ [160 - 450 s] per run

6.4.2 Heterogeneous Implementation

The objective of the hardware testing in this section is to demonstrate that the proposed MISS scheduling algorithm can work with real world devices and hardware, and that the data can be split transparently across multiple RATs.

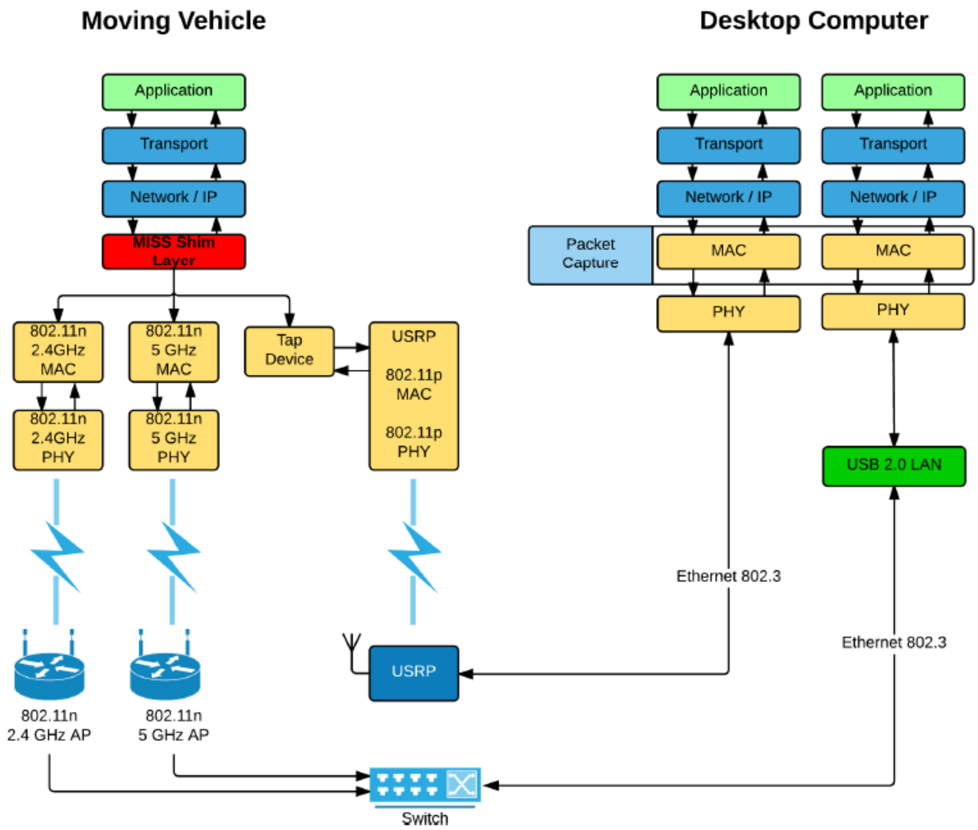


Figure 6.12: Layer Stack of hardware test elements

Testing Parameters and Setup

The algorithm was implemented and tested on a single user node with 3 RATs. The testing parameters and setup are described in Table 6.4. The Wi-Fi ① 802.11p 5.9 GHz implementation is performed via Ettus Research USRP boxes. The data rate of Wi-Fi ① 802.11p 5.9 GHz is limited to 20 kbps rather than 6 Mbps as the standard indicates, due to buffer configuration on the receiver side. This limitation does not affect the other RATs. Increasing the data rate to the specification standard is an area for further work. The data rate of Wi-Fi ② has been limited to 19.5 Mbps and that of Wi-Fi ③ to 58 Mbps. The RATs work on different frequencies and there was no channel interference. The channel and Tx Gain were left by default from the APs configurations. No authentication has been implemented and a static IP address scheme is used. The APs were arbitrarily spaced at 10 m from each other. The speed of the node was the average speed once the experiments have been performed. The testing time was the observed value necessary to complete the circuit, depending on the chosen path. As in previous experiments, the packet payload size of 1448 bytes was

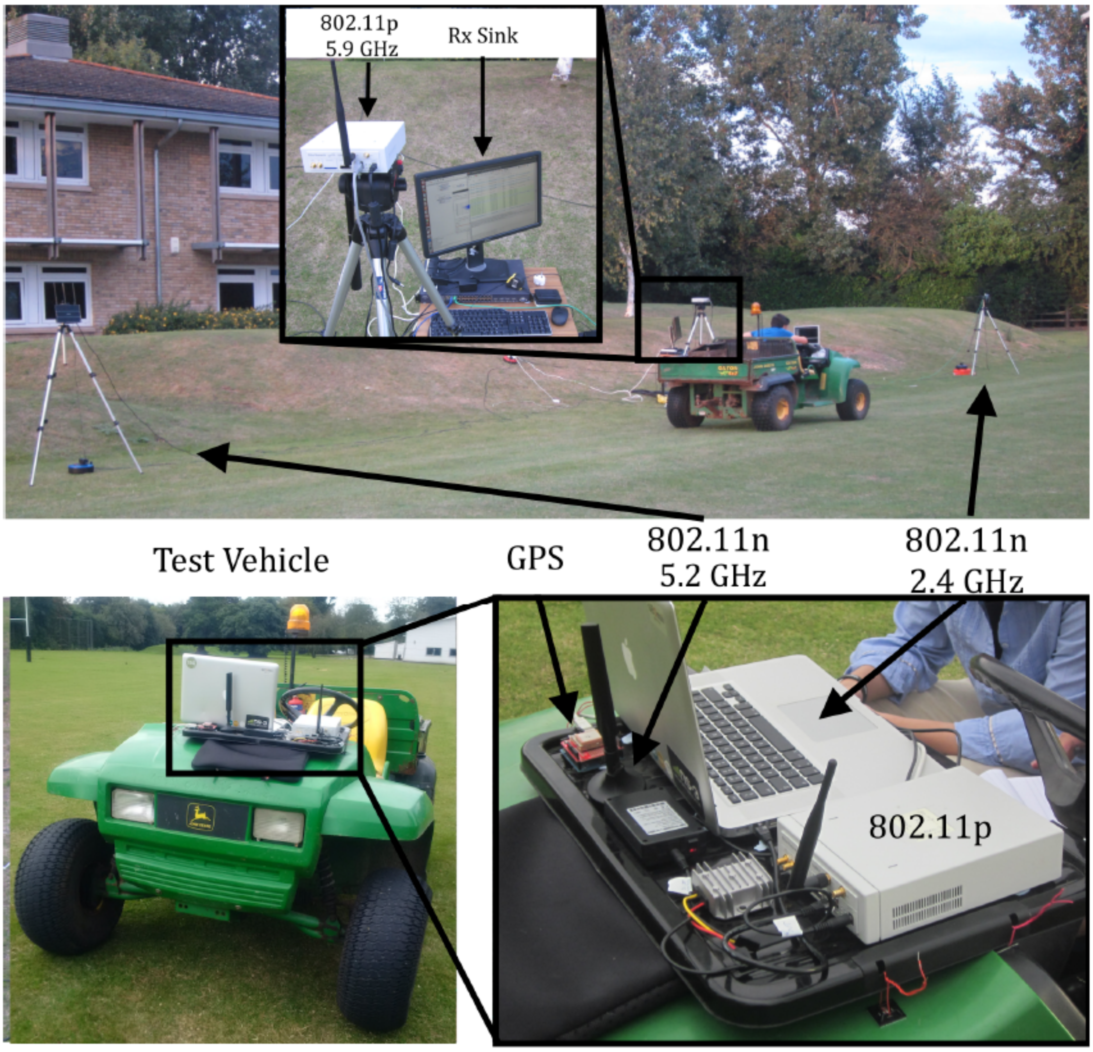


Figure 6.13: Pictures of Heterogeneous Testing material and environment

chosen to avoid fragmentation at the IP layer (1500 bytes MTU - 52 bytes IP header). For the safety packets, the 200 bytes value from the Basic Safety Messages (BSM) was chosen.

Figure 6.12 provides a layered stack view of the hardware and the connections between the elements. The USB Ethernet adapter in Figure 6.12 has a 400 Mbps limitation because of the USB 2.0. Tests with data rates above 200 Mbps per access point are therefore not conclusive.

No automated obstacle avoidance or autonomous driving was involved in these initial heterogeneous tests and a different vehicle than the ITS quad-bike was used. The test vehicle was equipped with a GPS module to trace the positions across the field. Two routes were taken by the vehicle, depending on the

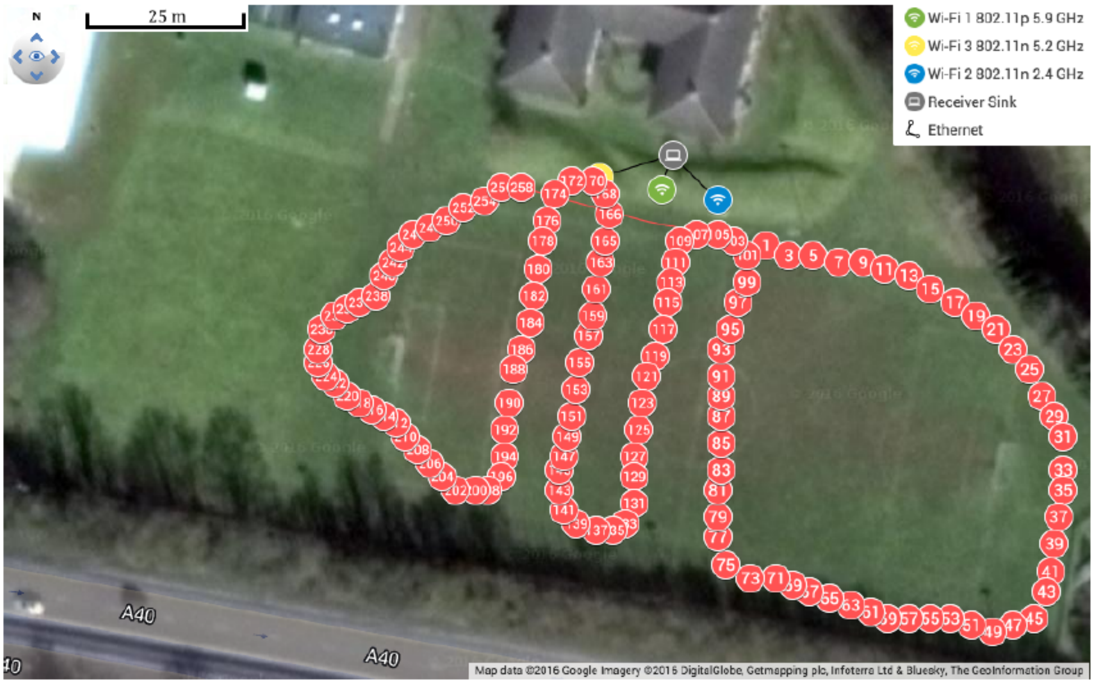


Figure 6.14: Map of Short Path Heterogeneous Testing Environment on Wheatley Campus

Figure 6.15: Map of Long Path Heterogeneous Testing Environment on Wheatley Campus

number of tested RATs. When only Wi-Fi ② and ③ were used, the short route (SR), depicted in Figure 6.14, was taken with an average completion time of the route in 250 - 300 s. When all RATs were used, the longer route (LR), depicted in Figure 6.15, was taken with an average completion time of the route in 450 s. Both paths have as start and end point Wi-Fi ① (green). Images of the vehicle, hardware and setup from the testing can be seen in Figure 6.13.

Simple tests (ping and dummy packet transmission) have been performed with LTE but the interface was not used for the Hardware Testing as it would have required creating an experimental setup with an Internet gateway. This has been left for future work.

Results and discussion

The difference between Parallel with Redundancy (Figure 6.16) and Parallel without Redundancy (Figure 6.17) can be seen in the number of received packets with double the amount of data for the Parallel with Redundancy than Parallel without Redundancy ($\approx$ 8 Mbps vs. $\approx$ 4 Mbps). The second item in the graphs (Wi-Fi 802.11n 5.2 GHz) has been plotted as bar values rather than linear in order to better assess the difference between the two RATs. The drop of Wi-Fi ③ at the 45th second in Figure 6.16 is due to the vehicle getting out of range of the AP.

When all three RATs are used (Figure 6.18) the packets are distributed across all three RATs. The 'Total Rx Packets' (black line) represent the total received packets by the sink and it is the sum of the transmitted packets by the 3 RATs. It is to be noted that Wi-Fi 802.11n 5.2 GHz is mostly overlaid with Wi-Fi 802.11n 2.4 GHz. The Wi-Fi 802.11n 2.4 GHz line (dark blue) can be observed when the spikes from 802.11n 5.2 GHz occur. The spikes represent the 802.11n 5.2 GHz AP getting out of range. The packets that were not successfully transmitted remain in the transmission buffer and when the vehicle returned in the range of the AP, all the packets were transmitted. The 802.11p RAT (Wi-Fi ①) stops after the 190th second because of a software buffer error, independent of the shim layer, within GNU Radio.

These behaviours, except for the software buffer error, are as expected from the MISS scheduling algorithm and the shim layer. The tests have validated that the shim layer can be implemented on hardware.

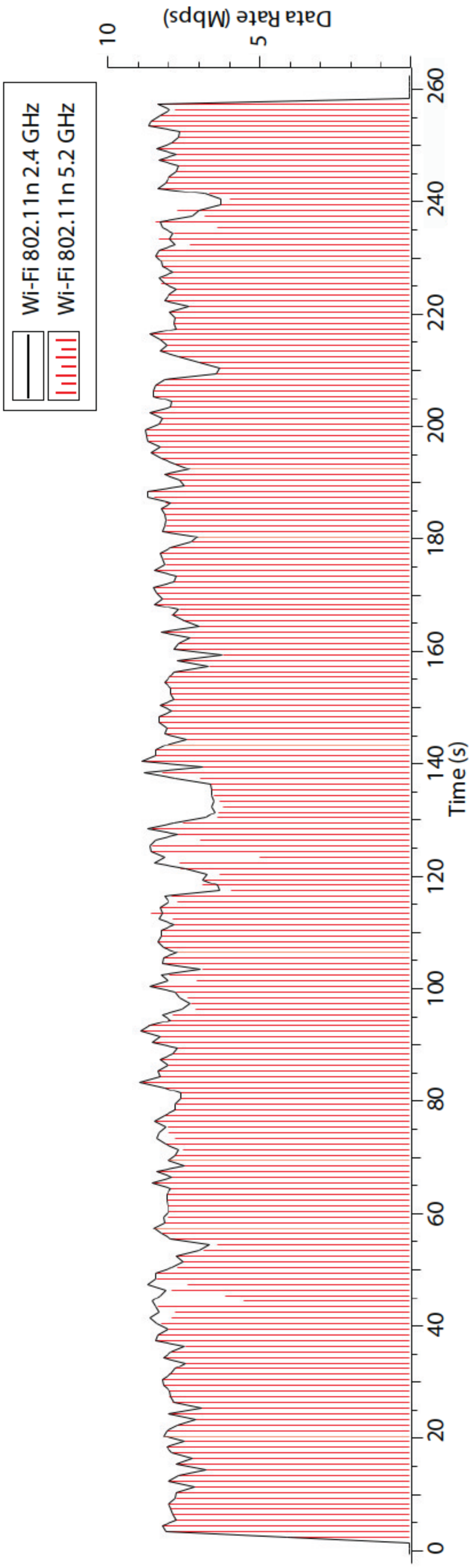


Figure 6.16: Parallel with Redundancy on the Short Route with Two RATs: Wi-Fi (2) and Wi-Fi (3)

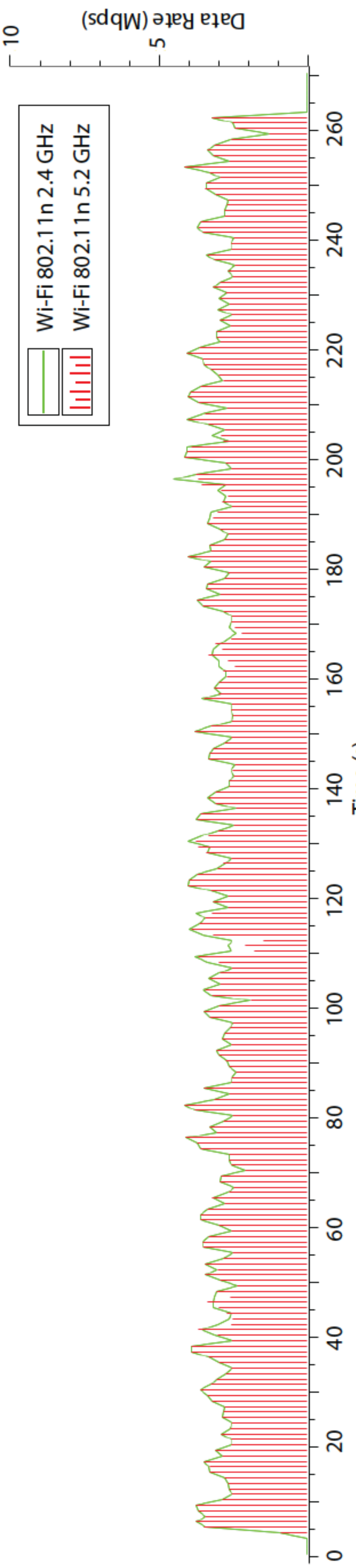


Figure 6.17: Parallel without Redundancy on the Short Route with Two RATs: Wi-Fi (2) and Wi-Fi (3)

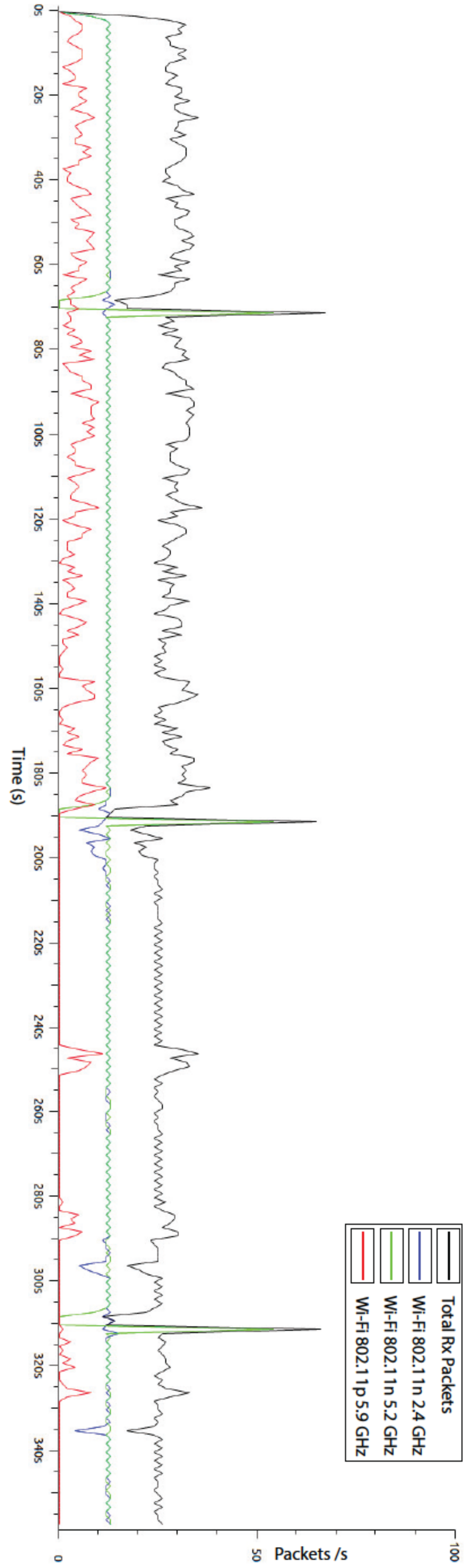


Figure 6.18: MISS Scheduling System on the Short Route with all three RATs

6.5 Summary

In this chapter, the network selection uplink scheduling algorithm was further evaluated in relation to various mobility types. Realistic simulations were performed by generating realistic mobility traces of Oxford and overlaying the real locations of existing Wi-Fi Access Points. An Intelligent Transport Systems test bed was developed to assess the shim layer communication capabilities via heterogeneous wireless systems. Initial tests have been performed with a single user node and the feasibility of obstacle avoidance using low cost equipment with a remote image processing approach in a real time environment has been shown. It was also shown that the heterogeneous wireless system with the proposed algorithm can be practically implemented and can work with real world devices and hardware. One large area that needs investigation is the comparison between the simulation results and the hardware results.

Chapter 7

Conclusions and Future Direction

"It always seems impossible until it's done"

[Nelson Mandela]

The main motivation behind this research work is that the availability of multiple independent Radio Access Technologies can be used to improve spectral efficiency and availability. Providing reliable wireless communication capability between vehicles and between vehicle and infrastructure is the key to the future success of Intelligent Transport Systems and automated vehicles. Applications will include improved information to drivers, enhanced safety features, platooning, support for autonomous driving and infotainment. Effectively managing resource allocation in such a complex environment requires a shift from traditional centralized mechanisms toward user-centric and self-optimizing approaches. Multiple wireless technologies have been developed that respond to different needs, short-range/long-range, high bandwidth/low latency but no single RAT can meet all these requirements with the vehicular network at its core.

In this thesis, a novel scheduling algorithm was proposed at an intermediate layer between the MAC and Network layer that can schedule packets to different RATs transparently. The Multiple Interface Scheduling System (MISS) sends information over multiple radio access technologies without modification of the existing standards. The algorithm accommodates different performance metrics and can adapt its decisions based on user-specified profiles. The scheduling algorithm scoring is a combination between a compensatory algorithm and non-compensatory algorithm: a compensatory algorithm is adapted by adding minimum cut-off values. Another advantage is that a single IP address can be used to identify a node due to the presence of a single Network layer. In addition, the same network security mechanisms implemented by individual wireless technologies at the lower layers and data security solutions at the upper layer can still be deployed. The considered RATs are cellular, infrastructure based Wi-Fi (802.11n 2.4 GHz and in the 5 GHz band) and the vehicular Wi-Fi 802.11p.

In the current state, one of the limitations of the shim layer is that it can provide a transparent heterogeneous connection only for the uplink. The focus is set on the uplink rather than the downlink as several emerging applications treat vehicles as data sources. Similarly, providing a heterogeneous uplink does not require any modifications to the standards and the RATs can be managed by different operators. Providing a heterogeneous link on the downlink requires that the different RATs are provided and managed by the same operator and a user scheduling approach is performed on the operator side.

The experiments demonstrated that it is possible to schedule multiple packets over different wireless technologies, which are not provided by the same operator. For a given scenario, higher availability and throughput can be achieved and packets can be prioritized based on user profiles with no modification of standards. In terms of scalability, the intermediate shim layer proved to be a suitable approach for supporting connectivity by increasing the availability of uplink connection with the current infrastructure. Simulations with real-world data have also shown the benefits of using the shim layer in relation to different mobility types (walking, driving, cycling) within an urban environment and with the existing Wi-Fi infrastructure.

The shim layer can also be beneficial in a non-cooperative multi-user environment, with a high number of users that all have the shim layer, but the underlying RATs limitations are also limiting the shim layer performance as the number of users increase. The performance is higher in terms of packet delivery ratio and delay compared to a non-shim layer approach for both saturated and non-saturated environments.

MISS and the shim layer were also implemented on hardware to show the feasibility of such a system in a real-world environment. Tests were performed on campus with a moving vehicle with three different RATs - Wi-Fi 802.11n 2.4 GHz, Wi-Fi 802.11n 5.2 GHz and Wi-Fi 802.11p 5.9 GHz - and showed that data can be split transparently across multiple RATs. The shim layer can be beneficial for a heterogeneous wireless network in Intelligent Transport Systems. Such an approach is not only valid for heterogeneous vehicular networks but can be used by mobile devices where the goal is to upload information from different portable devices at any time and anywhere.

7.1 Future Direction

Improvement to the current work can be made on several fronts. The first is implementing and testing with other RATs such as Bluetooth, VLC or possibly satellite. Integrating a transparent heterogeneous solution in the shim layer for the downlink is an area that would enhance this work. Currently, end devices can be upgraded via a software update to include the shim layer. Software Defined Networks (SDN) in the cloud could be used to provide a similar technology agnostic solution for the downlink with no modification of the existing wireless standards.

In terms of simulation, more extensive performance evaluations can be done to assess the impact of the MAC overhead or the difference between a packet by packet and block processing approach. A comparison between UDP and TCP is another set of tests that would require particular attention. In general, the use of real traffic traces (Cologne Vehicular Traces) would enhance the simulation work.

Cellular simulations are one of the areas that could not be covered by this work and could also be performed. It is to be seen how variation on the parameters and/or profiles of the users under the same simulated scenario (e.g. half the users use the shim layer with MISS and the other half are equipped with other non cooperative algorithms) affects the overall network performance. Furthermore, comparing the shim layer with other heterogeneous solutions, working at different layers, would be an interesting study.

Cooperative applications are a potential area of study. However, they are more difficult to implement and assess on hardware as they require large penetration rates in order to assure their functionality, making the first steps towards their deployment unattractive. In a similar way, devising a system that ensures backward compatibility for legacy technologies such as IPv4 is one of the main challenges that still needs to be addressed.

The emergence of the 'Internet of Things' with low power nodes can be an opportunity for the profile based shim layer. The nodes mainly send information and might have different RATs available depending on their mobility but are restricted by their power consumption.

In terms of hardware testing, remote image processing with heterogeneous networks is a multidisciplinary area of study that can provide novel results. Finally, testing the shim layer with multiple users on hardware is one of the key paths for a possible implementation of the proposed approach in future Intelligent Transport Systems.

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