EXPERIMENTAL EVALUATION OF INTEGRATED DSRC AND WI-FI SYSTEMS FOR INTELLIGENT TRANSPORTATION SYSTEMS

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DECLARATION

I declare that this is my work, and this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any other university or institute of higher learning, and to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

The high initial and maintenance costs of standard Dedicated Short-Range Communications (DSRC) and cellular V2X systems pose a significant barrier to the implementation of Intelligent Transportation Systems (ITS), particularly in low- and middle-income countries where road safety is a critical requirement. This thesis addresses the necessity for cost-effective V2X solutions by developing and experimentally evaluating a DSRC/Wi-Fi integrated communication system. The system leverages low-cost Wi-Fi (IEEE 802.11 n) technology, which shares protocol similarities with DSRC, utilizing economic devices such as the ESP32 System-on-Chip (SoC). The cost of integrating the Wi-Fi subsystem is less than 30 USD.

The proposed architecture integrates commercial DSRC devices with the low-cost Wi-Fi subsystems, connected via an Ethernet link, to deliver information for applications such as Active Road Signs (ARS). System performance was evaluated using critical vehicular communication metrics:

- Packet Delivery Ratio (PDR)
- Maximum Range (MR)
- Effective Range (ER)
- Packet Interarrival Time (PIT)

Empirical evaluation demonstrated that the system is a viable solution for many ITS applications, confirming a MR above 300m and an Effective Range (ER), defined as the range where PDR is above 50%, of approximately 200m. Crucially, the probability of situation awareness blackouts (PIT > 1s) was found to be negligibly small. To assist designers in selecting optimal parameters, a model was developed using a Bi-directional Long Short-Term Memory (Bi-LSTM) neural network to predict system performance (PIT) based on variables such as distance, speed, RSSI, and beacon interval. This work confirms that the novel dual communication system offers a practical, low-cost pathway for extending V2X capabilities.

Keywords: Integrated Communications for ITS Applications, Intelligent Transportation Systems, Active Road Signs, Dedicated Short-Range Communications, DSRC / Wi-Fi Integrated Systems, Vehicle-to-Everything (V2X) communications

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List of Abbreviations

AODV Ad hoc On-Demand Distance Vector
ARS Active Road Signs
AU Application Unit
BSM Basic Safety Message
C-ITS Cooperative Intelligent Transport Systems
C-V2X Cellular Vehicle-to-Everything
CCH Control Channel
COTS Commercial Off-The-Shelf
CSMA/CA Carrier Sense Multiple Access with Collision Avoidance
D-OBU DSRC On-Board Unit
DSRC Dedicated Short-Range Communications
ER Effective Range
ETSI European Telecommunications Standards Institute
FTP File Transfer Protocol
GPRS General Packet Radio Service
GPS Global Positioning System
H-RSU Hybrid Roadside Unit
I-I2V Integrated Infrastructure-to-Vehicle
I-V2V Integrated Vehicle-to-Vehicle
I^2C Inter-Integrated Circuit
ICA Intersection Collision Avoidance
IP Internet Protocol
IPv6 Internet Protocol Version 6
ITS Intelligent Transport System
LTE Long Term Evolution
MAC Media Access Control
MCU Microcontroller Unit
MR Maximum Range
NGV New Generation V2X
NLOS Non-Line-of-Sight
NoW Network on Wheels
OBU On-Board Unit
OCB Outside the Context of the Basic Service Set
PCB Printed Circuit Board
PDR Packet Delivery Ratio
PIT Packet Interarrival Time
PPDU Physical Protocol Data Unit
PSK Pre-Shared Key
RF Radio Frequency
RSA Roadside Alert
RSSI Received Signal Strength Indicator
RSU Roadside Unit
SBC Single-Board Computer
SCH Service Channel
SoC System-on-Chip
SPI Serial Peripheral Interface
SUMO Simulation of Urban Mobility
TCP Transmission Control Protocol
UART Universal Asynchronous Receiver-Transmitter
UDP User Datagram Protocol
USB Universal Serial Bus
UTC Coordinated Universal Time
V2I Vehicle-to-Infrastructure
V2V Vehicle-to-Vehicle
V2X Vehicle-to-Everything
VANET Vehicular Ad Hoc Network
W-Beacons Wi-Fi Beacons
W-OBU Wi-Fi On-Board Unit
WAVE Wireless Access in Vehicular Environments
WLAN Wireless Local Area Network
WSMP WAVE Short Message Protocol

CHAPTER 1

INTRODUCTION

1.1 Research Background

Road safety is one of the most important aspects of past, present and future transportation systems. According to statistics [16], [17] close to 4000 lives are lost each day due to vehicular accidents globally. Another 20 to 50 million people suffer injuries annually. More than 90% of these are traced back to low- and middle-income countries. According to sources [17], these occur due to distracted drivers, unsafe vehicles and road infrastructure, and slow emergency services.

This calls for a system that can exchange information among the participants of transportation systems in an efficient and timely manner using new technologies and, in turn, make the overall transport system safer, efficient, and sustainable. Such systems are named ITS [18]. ITSs achieve their purpose through improving the availability of information to drivers, infrastructure, and vulnerable road users. They are enabled with various advanced technologies capable of monitoring transport systems, predicting, and taking proper and timely action.

These ITSs leverage Vehicle-to-Everything (V2X) communications to provide a multitude of safety and entertainment applications. In these ITSs, a Vehicular Ad Hoc Network (VANET) will be developed among the on-board units (OBUs) and road-side units (RSUs) to exchange critical information.

At the beginning of the 21st century, both United States Federal Communications Commission and European Telecommunications Standards Institute (ETSI) allocated spectrums in the 5.9GHz band for ITSs. This was named Dedicated Short-Range Communications (DSRC) [19]. This was later on standardized as IEEE 802.11p, for use predominantly in automotive, wireless communication systems. Also, with the introduction of peer-to-peer communication capability in cellular technologies such as 4G, Long Term Evolution (LTE), and 5G, many researchers [20–22] started to develop ITS applications using these technologies as well. Hence, DSRC with 4G LTE and 5G technologies dominate the ITS telecommunication applications. Although they are properly equipped to handle the requirements of ITS applications, they have very high initial and maintenance costs. Therefore, for ITSs to be a viable solution for low and middle-income countries, the underlying technology should be more cost effective. One promising solution is the use of dual communication technologies where possible. [23].

Using Wi-Fi (IEEE 802.11 b/g/n) seems promising, due to its protocol similarity to DSRC and the wide availability of low-cost devices. However, it has its shortcomings compared to DSRC [24, 25], such as connection establishment delays, security issues, issues with range, etc. This research focuses on developing a DSRC/Wi-Fi joint communication mechanism and evaluating its performance and suitability for ITS applications. The proposed joint system is evaluated using performance metrics similar to [6], which are Packet delivery ratio (PDR), MR and ER, Packet delay, Inter arrival statistics, through experimental methods.

Finally, a model will be developed for the novel communication system using the experimental data. This is to help with designing and implementing the novel system in various ITS applications.

1.2 Objectives

The purpose of the research is to develop and experimentally evaluate a DSRC / Wi-Fi integrated communication system that is capable of catering to ITS applications. A class of applications is chosen for design and evaluation purposes, after a brief survey of the ITS applications vital for Sri Lanka. The specific research objectives are:

- Survey on the applicability of integrated DSRC/Wi-Fi ITSs in Sri Lanka.
- Design/propose and implement the overall system architecture for the integrated DSRC/Wi-Fi communication system with necessary specifications.
- Experimentally evaluate the system performance and develop a system model to predict the performance of the novel system.

1.3 Methodology

The methodology is represented as 4 milestones,

- Literature Review and Research Framework Definition.
- System Architecture and Component Design.
- System Implementation and Experimental Data Collection.
- Model Development and Performance Analysis

Further, the research is planned to be conducted in 3 phases to achieve the mentioned milestones. These are shown in Fig. 1.1. A comprehensive literature survey was conducted in the fields mentioned in Fig. 1.1. Then, a system architecture was designed and implemented using a System-on-Chip (SoC) device. A thorough data collection campaign was conducted in a controlled environment, and a model was developed to predict the system's performance using the collected data.

1.4 Research Significance

With the increasing number of vehicles on roads, ITSs have become an absolute necessity for transportation systems. The value of ITS has become evident in numerous trials conducted, particularly in Europe [26], USA [27], and Australia [28], as well as integration of V2X into the automobile industry.

However, the low and middle-income countries, where a vast amount of road accidents take place, are unable to invest in DSRC or Cellular Vehicle-to-Everything (C-V2X) systems.

As a large amount of outdated vehicles are being used in these countries than in developed countries. As a result, the safety benefits of ITSs remain inaccessible to a large portion of road users. These challenges highlight the need for low-cost communication alternatives that can operate reliably in vehicular environments and be retrofitted to older vehicles to significantly extend the reach of ITS applications beyond high-income settings.

1.5 Organization of the Thesis

This thesis is compiled as follows. The **first chapter** provides an introduction to the research and presents the objectives and methodology of the research. The **second chapter** presents the insights obtained through a review of relevant literature. The **third chapter** describes the design and implementation of the communication system and the **fourth chapter** presents the experimental evaluation of the designed systems with recommendations on feasible applications for the integrated system. The **fifth chapter** provides details on the system modelling, while the **sixth chapter** presents the overall conclusion and recommendations.

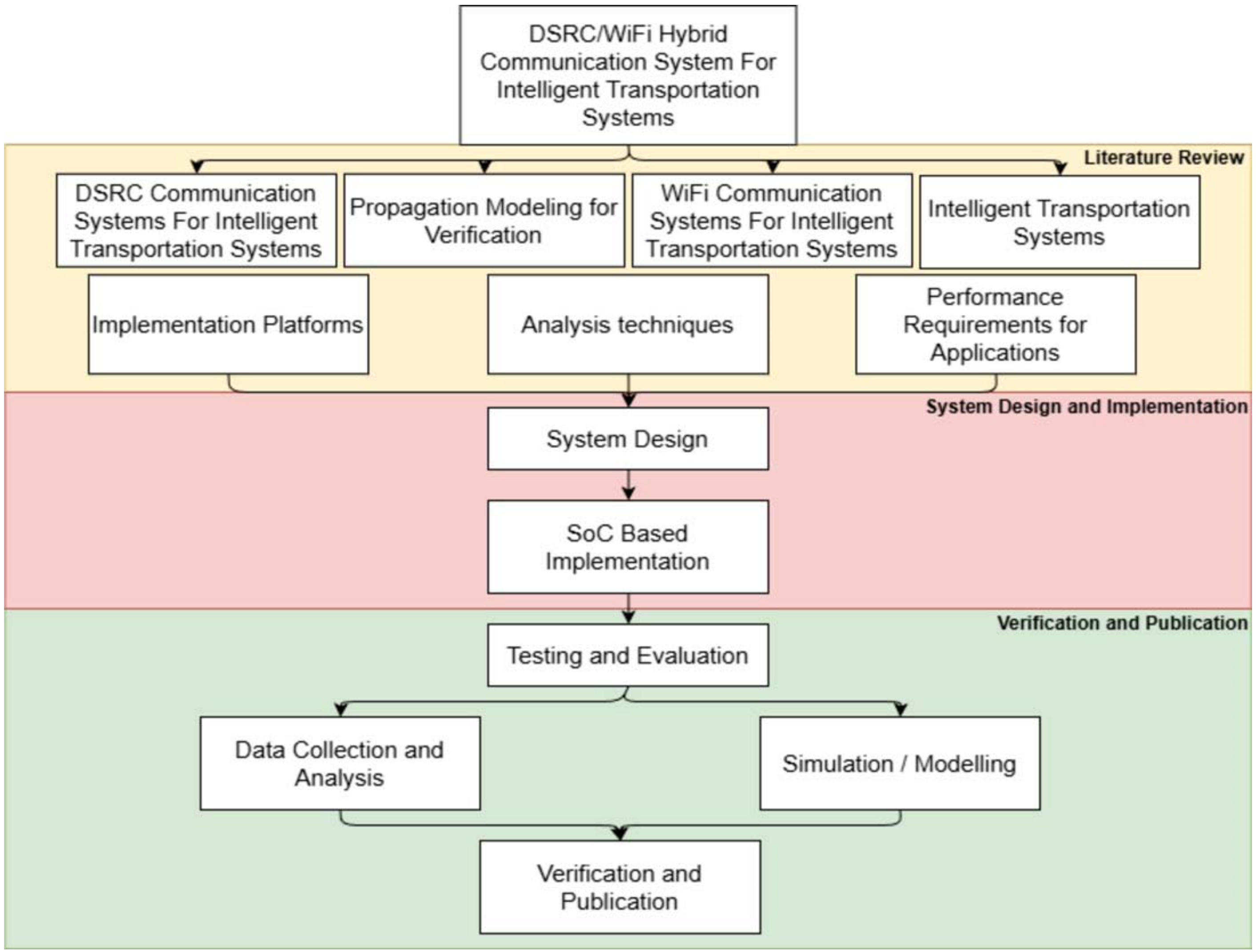


Fig. 1.1: Research Methodology

CHAPTER 2

LITERATURE REVIEW

2.1 Intelligent Transportation Systems (ITS)

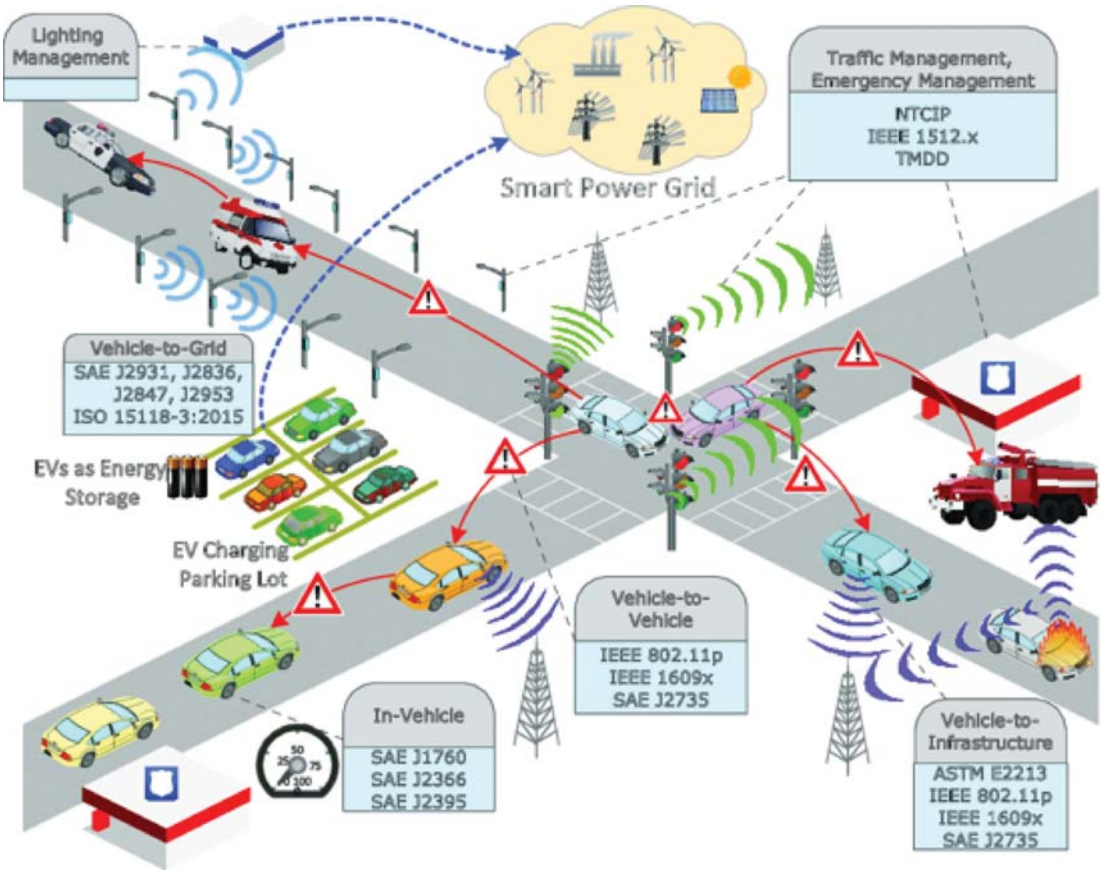


Fig. 2.1: Intelligent Transport System and Smart City [1]

Intelligent Transport Systems are a collection of applications relating to different modes of transportation, that use cutting-edge innovative technologies to keep the actors of those systems better informed and in turn, safe and improve the systems efficiency. Fig. 2.1 shows a few ITS applications which are becoming popular in the world. They use advanced technologies to sense, monitor and control transport systems, addressing issues such as congestion, fuel efficiency, safety, and pollution among others.

Even though ITSs sound like 21st-century technology, these have been developing since the 1930s [2] mostly in the United States, Europe and Japan. These developments can be identified as three phases; preparation (1930-1980), feasibility study(1980-1995) and finally the application development phase [2].

Some of the most notable systems in these periods are,

- Comprehensive Automobile Traffic Control System (CACS) [2], [29].
- Autofahrer Leit und Information System (ALI) [2].
- Program for European Traffic with Efficiency and Unprecedented Safety [2] (PROMETHEUS).
- ARGO project [2], [30].
- Dedicated Road Infrastructure for Vehicle Safety in Europe (DRIVE) [29].

From the 1930s to the early 1980s, the existing technologies have been unable to facilitate the ITS applications. After the enabling technologies were developed, from the 1980s onwards, many projects were initiated to develop the technical foundation for ITS applications, which were funded by both governments and industry partners in the USA, Japan, and Europe [2]. Fig. 2.2 shows a few major projects in the aforementioned regions and their timelines.

Since 1995, there has been a significant development in ITS applications all around the world. Figueiredo,L [2] et. al., categorize these into six categories as summarized in Table 2.1.

TABLE 2.1: ITS application categories and example applications.

ITS application category	**Example application**
Advanced Traffic Management Systems (ATMS)	Realtime traffic monitoring, Highway advisory radio, etc.
Advanced Traveller Information Systems (ATIS)	WEBFLOW32, Google maps, etc.
Commercial Vehicle Operation (CVO)	Fleet management, Hazardous Material Planning and Incident Response, etc.
Advanced Public Transport Systems (APTS)	BUSVIEW, BUSAWARE, etc.
Advanced Vehicle Control Systems (AVCS)	Advance cruise control, Automated steering control, etc.
Advanced Rural Transport Systems (ARTS),	ATIS, ATMS and APTS systems specilized for rural areas (steep roads, blind corners, etc.)

Electronic toll collection, navigation and guidance systems, autonomous vehicles, automated parking management systems are just a few of the ITS applications. They have become more effective and affordable with the continuing development of enabling technologies.

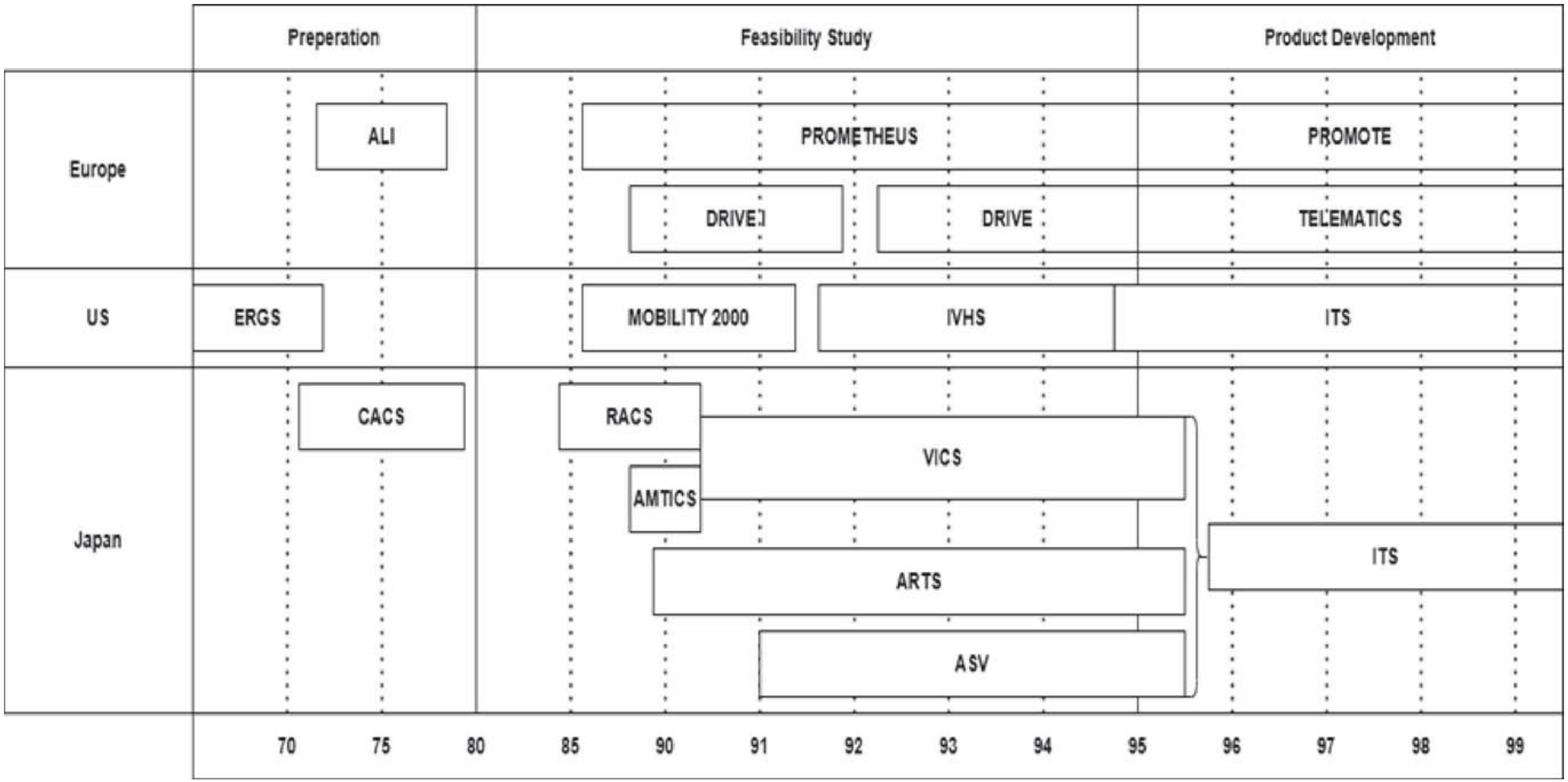


Fig. 2.2: ITS Development Chronology [2]

2.2 Enabling Technologies

ITS applications are enabled using a variety of technologies. However, data acquisition, data processing, and communication are the basis of most ITS applications. The development and miniaturization of sensors, processors, and microcontrollers (MCUs) play a major role in the development of ITS.

2.2.1 Communication Technologies

A key enabler of ITS applications is Vehicle-to-Everything (V2X) communications. This implies the communication between vehicles and infrastructure, vehicles, pedestrians, networks, etc. As shown in Fig. 2.3, V2X communication technology enables the exchange of information among the components of transport systems.

- V2P - Vehicle-to-Pedestrian
- I2I - Infrastructure-to-Infrastructure
- I2N - Infrastructure-to-Network
- V2I - Vehicle-to-Infrastructure
- V2V - Vehicle-to-Vehicle
- V2N - Vehicle-to-Network

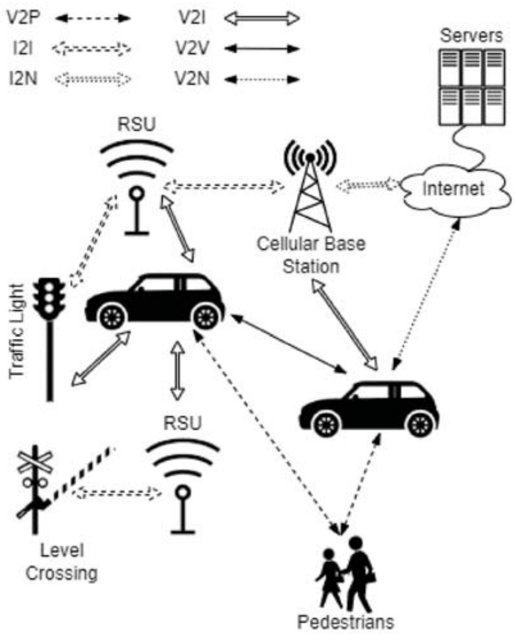


Fig. 2.3: V2X Communication

Many new communication technologies have been developed with the increasing interest in ITS applications, such as those based on IEEE 802.11 b/g/n (Wi-Fi), cellular (3GPP), and microwave communication (IEEE 802.16). However, IEEE 802.11p or DSRC and C-V2X have become prevalent in the ITS domain. Since these technologies are expensive and have low penetration, many researchers are currently experimenting with alternative and joint approaches [3, 8].

2.2.1.1 DSRC

IEEE 802.11 p

Among the IEEE 802.11-based technologies, DSRC was specially designed to be used in vehicular/high-speed environments. As summarized by John B. Kenney in [3], IEEE 802.11p operates in the 5.85GHz – 5.925GHz frequency range allocated by the Federal Communications Commission, i.e., the "5.9GHz band". It consists of 7 channels of 10MHz bandwidth and 5MHz guard bands as seen in 2.4.

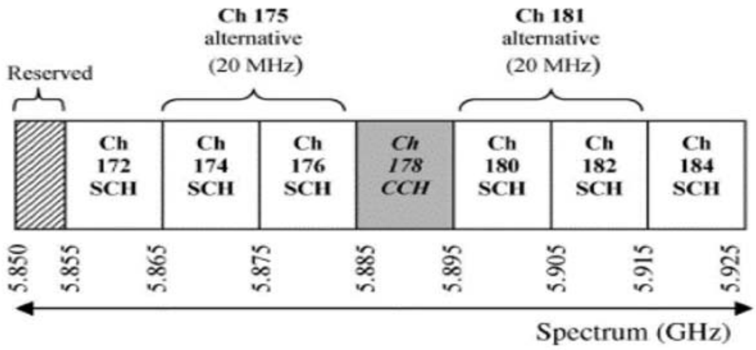


Fig. 2.4: DSRC Spectrum [3]

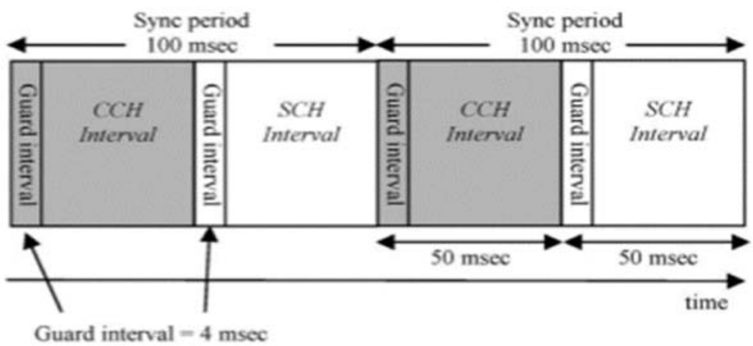


Fig. 2.5: DSRC Time Division [3]

These channels are capable of 6Mb/s communications speeds and distances up to 1000m. However, on some occasions, these 10MHz bands are combined into 20MHz channels as shown by Fig. 2.4. These channels are divided into two main categories, namely Service Channel (SCH) and Control Channel (CCH). Devices will switch between SCHs and CCHs periodically as shown in Fig. 2.5. Devices are assumed to have access to Coordinated Universal Time (UTC) through a Global Positioning System (GPS) device and are synchronized accordingly.

Devices that are offering services advertise themselves and the services in the CCH interval. If there are any interested receivers, they will communicate with the supplier in the SCH. They may use a special message type in Wireless Access in Vehicular Environments (WAVE), named WAVE Short Message Protocol (WSMP), or User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) with the Internet Protocol Version 6 (IPv6). While WSMP is used for safety applications, the TCP,UDP or Internet Protocol (IP) stack is used for non-safety applications. The channel switching functionality is defined in the IEEE 1609.4 protocol (Fig. 2.6).

Other major protocols in the DSRC protocol stack (Fig. 2.6) include;

- IEEE 1609.2 – Security service protocols.
- IEEE 1609.3 – Networking service protocols.
- SAE J2735 – Standard dictionary of message formats.

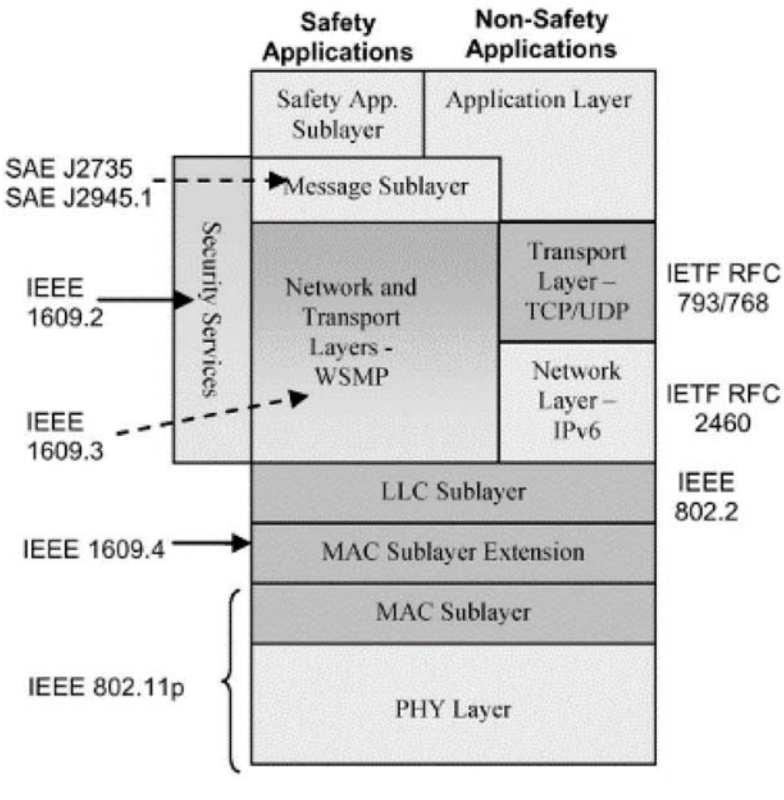


Fig. 2.6: DSRC Protocol Stack [3]

One prominent message type, that is defined in SAE J2735 is the Basic Safety Message (BSM). The content of this message type enables vehicles to exchange information with other vehicles in the vicinity. These messages contain the location, speed, type, and other valuable information about the transmitting vehicle. These BSMs are periodic messages, which are usually transmitted at a 10GHz rate. However, depending on the application, it might be increased or decreased. To state the obvious, any delays in the Vehicle-to-Vehicle (V2V) communication must be reduced. Therefore, Media Access Control (MAC) protocols of Wi-Fi were amended to operate purely in a broadcast mode without the need for authentication, association, and connection establishment. Further, the MAC layer parameters were amended to shorten the medium access delays encountered in dense vehicular environments.

Initially, BSMs were sent out in the CCH (channel 178). Since this is a periodic beacon, it was decided to use channel 172 just for BSM transmission and other vehicular crash avoidance messages. Therefore, it has been proposed that new vehicles should come equipped with a mandatory DSRC radio for BSM communications and another optional one for other communications.

IEEE 802.11 bd

While being built on the IEEE 802.11ad stack, IEEE 802.11bd is the fully backward-compatible next-generation evolution of IEEE 802.11p [11]. As this New Generation V2X (NGV) supports coexistence and interoperability with IEEE 802.11p, pre-existing systems and current developments will remain relevant and viable. Some of the most important features added are summarized in the Table. 2.2.

As mentioned previously, IEEE 802.11bd is designed as a fully backward-compatible evolution of IEEE 802.11p. This approach ensures a smooth and gradual transition from existing systems like ETSI ITS, thereby leveraging all already-existing deployments and roll-outs. This evolutionary design fully protects investments in existing IEEE 802.11p-based technologies, including ITS-G5 and DSRC road infrastructure.

To support mixed communication environments where IEEE 802.11p and NGV devices operate simultaneously, IEEE 802.11bd incorporates several specific mechanisms to guarantee coexistence, fairness, and interoperability:

- **Preamble and Waveform Compatibility**: To ensure coexistence, the newer IEEE 802.11bd waveforms begin with the same sequence used by existing IEEE 802.11p implementations, using the 10 MHz IEEE 802.11p preamble. This allows existing IEEE 802.11p devices to detect IEEE 802.11bd transmissions. By detecting this common preamble and deriving the packet duration (from the legacy signal information), existing stations can defer transmission to avoid collisions.

- **Legacy Transmission Capability**: Full access-layer interoperability is achieved because IEEE 802.11bd stations are capable of transmitting and receiving IEEE 802.11p Physical Protocol Data Unit (PPDU). Specifically, each NGV station must be capable of transmitting using the IEEE 802.11p-based 10 MHz PPDU format so that older ITS devices can receive the transmissions. In a mixed environment, enhanced Cooperative Intelligent Transport Systems (C-ITS) stations

TABLE 2.2: Comparison of IEEE 802.11p and IEEE 802.11bd Features [11, 12]

Feature	**IEEE 802.11p**	**IEEE 802.11bd**
Max Data Rate	∼27 Mbps	Up to ∼180 Mbps (with two spatial streams)
Error Correction	Binary Convolutional Coding (BCC)	Low-Density Parity Check (LDPC), offering ∼2–3 dB sensitivity improvement
Channel Bandwidth	Fixed 10 MHz	Supports 10 MHz and 20 MHz (via bonded channels)
Antenna Technology	No MIMO capability	2×2 MIMO support, enabling higher unicast throughput. However, broadcast does not support MIMO
High-Speed Channel Tracking	Pilot-based channel estimation	Midamble insertion for enhanced tracking at high mobility depending on configuration and environment
Range & Robustness	Standard modulation and coding	Dual Carrier Modulation (DCM) and adaptive repetitions, extending range by up to 3×
Positioning Features	No ranging support	Enhanced Fine Timing Measurement (FTM) based ranging to complement.
Overall Performance	Baseline reference	Up to 3× higher throughput and up to 3× extended range under typical NGV configurations.

detecting nearby IEEE 802.11p stations will transmit all safety-related messages using the IEEE 802.11p-based access layer so that existing stations can decode the content.

- **Fair Channel Access**: Fairness by design is required so that all devices, regardless of generation, have the same opportunities to access the channel. This requirement is fulfilled because IEEE 802.11bd stations continue to rely on the established Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) procedure. NGV stations use a "Listen Before Talk" mechanism and adhere to the same minimum sensitivities for clear channel assessment as specified in IEEE 802.11p.

In such a mixed operational environment, where devices are operated simultaneously, the control of both existing and enhanced features is managed on a message-by-message basis, by the Multi-Channel Operation entity. The continuous operation of both technologies forms mixed communication clusters where the timing behaviour and reliability of V2X messages remain critical considerations.

Although IEEE 802.11bd is the next evolutionary step of IEEE 802.11p, this research on integated Wi-Fi and DSRC communication remains highly relevant for several reasons.

- IEEE 802.11bd is still in the early deployment phase, and commercially available 802.11bd-enabled devices are extremely limited, whereas IEEE 802.11p continues to dominate deployed ITS infrastructure worldwide.
- Since 802.11bd must remain fully backward compatible with 802.11p, legacy DSRC systems will operate alongside 802.11bd for many years, particularly in cost-sensitive regions where replacing hardware is impractical. In such environments, Wi-Fi remains an attractive complementary technology due to its widespread availability, low cost, and configurability.

Therefore, Wi-Fi and DSRC joint solutions will continue to provide a practical pathway for extending the spread of ITSs within a larger demographic.

2.2.1.2 DSRC Based Implementations and Experiments

- Implementations

  Network on Wheels (NoW) [4] is one early but complete implementation of a DSRC-based intelligent transportation system which is the successor to FleetNet [31], and SOFTNET [32]. In this, both DSRC and Wi-Fi are used for safety and infotainment applications.

  Vehicles are equipped with an On-Board Unit (OBU) for communication activities. These OBUs provide an interface that the authors call the Application Unit (AU). These units can communicate with each other and the Roadside Unit (RSU). RSUs are equipped to provide roadside alerts and warnings, OBU message dissemination and OBU message store-and-forward when connectivity is sparse. For the RSU and OBU devices, commercial Wireless Local Area Network (WLAN) chips that use the Multiband Atheros Driver for Wi-Fi (MADWi-Fi) driver have been used. This driver was modified so that it would use the 5.9 GHz frequency band and support the IEEE 802.11p protocols.

  With this prototype system, applications such as forward-collision warning, emergency vehicle warning and a host of other safety applications were implemented

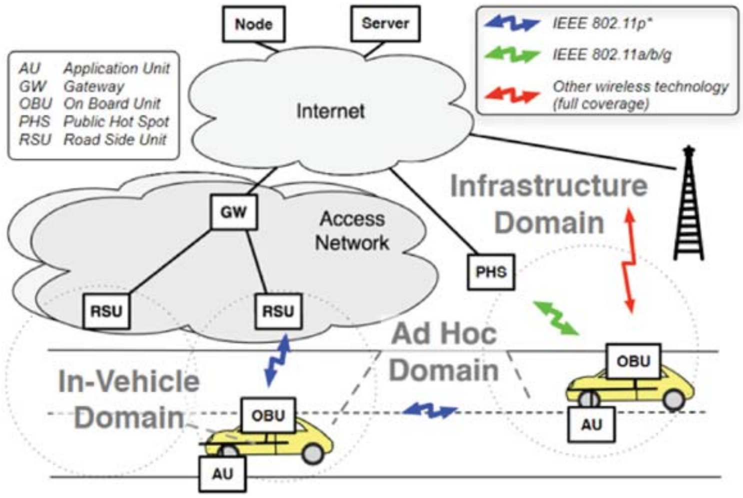


Fig. 2.7: NoW System Architecture [4]

by the authors. As for the Wi-Fi, it was used for infotainment applications, such as MP3 music downloading and drive-thru payments.

Since *NoW*, there have been many real world implementations and pilot deployments such as in Europe [33] , China [34] and in the United States [35].

- Experiments

  Experiments have been conducted using both empirical and simulation data.

  Fitah et al [5] presents a simulated comparison between IEEE 802.11p (DSRC) and IEEE 802.11a (Wi-Fi 2) in a couple of traffic scenarios using Network Simulator 2 (NS-2), OpenStreet Maps and Simulation of Urban Mobility (SUMO). The packet delivery ratio (PDR), end-to-end delay and average throughput have been compared.

  A map of the road network of the city of Casablanca(Fig. 2.8) extracted from OpenStreetMap is simulated in SUMO software with DSRC model using the Network Simulator 2.35(NS-2.35) software. As shown in Fig. 2.9 one scenario models the highways and trunk roads that serve the city of Casablanca. In the second scenario, other roads in the city are considered. 100 seconds of File Transfer Protocol (FTP) transmissions between vehicles, travelling in the same and opposite directions were considered. With Ad hoc On-Demand Distance Vector (AODV) routing, the Two-Ray-Ground propagation model and a range of 500m. It is observed that DSRC performs better in highway scenario, than the residential scenario while the IEEE 802.11a behaves inversely. Also, it can be noted that, in all three aspects considered, IEEE 802.11p surpasses the performance of IEEE 802.11a.

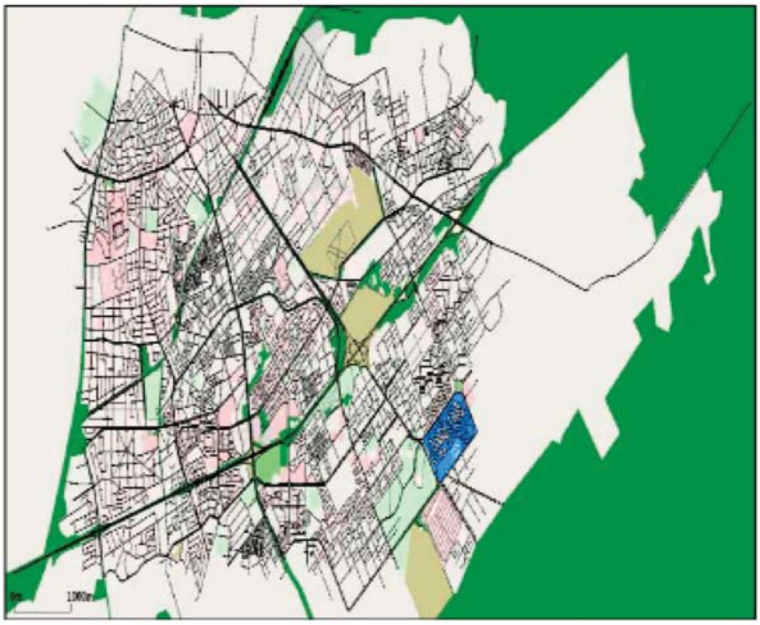


Fig. 2.8: City of Casablanca [5]

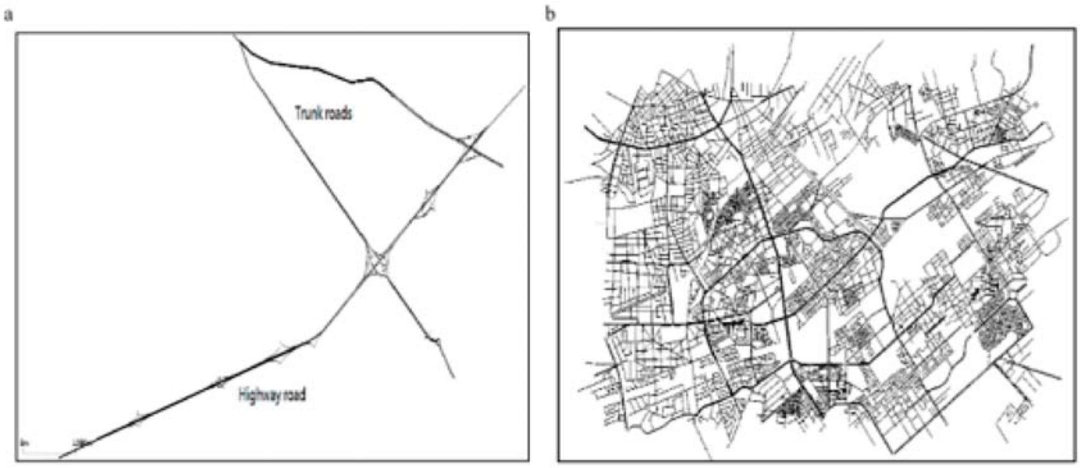


Fig. 2.9: "(a) First Scenario: Highway and Trunk Roads;
(b) Second Scenario: Primary, Secondary, Tertiary and Residential Roads" [5]

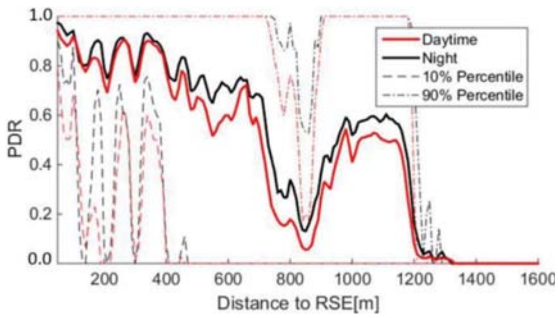
Another comprehensive, empirical evaluation has been conducted by X. Huang et al. The authors have collected data from RSU devices over a period of 933 days starting from the 24th of August 2012. With this data, they evaluate the performance of a DSRC-based Vehicle-to-Infrastructure (V2I) communication in various environmental scenarios and observe the factors that hinder performance of the system. The authors of the paper uses **PDR**, **Maximum Range (MR)**, **Effective Range (ER)** as performance metrics. The ER is defined as the range where PDR is held above 50%. Authors have compared the considered several scenarios and observed the variation of PDR as shown in Fig. 2.11.

(a) PDR for Highway and Residential Scenarios [5]

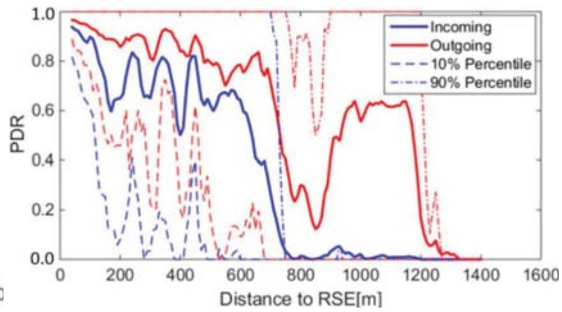
(b) Average Delay for Highway and Residential Scenarios [5]

(c) Average Throughput for Highway and Residential Scenarios [5]

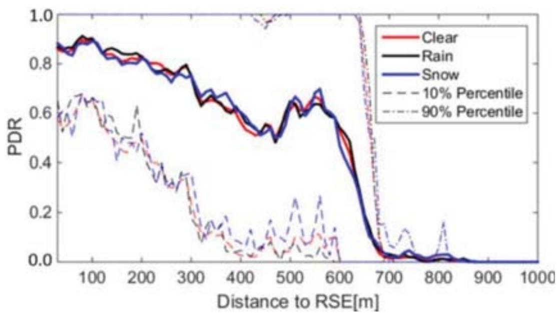
Fig. 2.10: Results in [5]



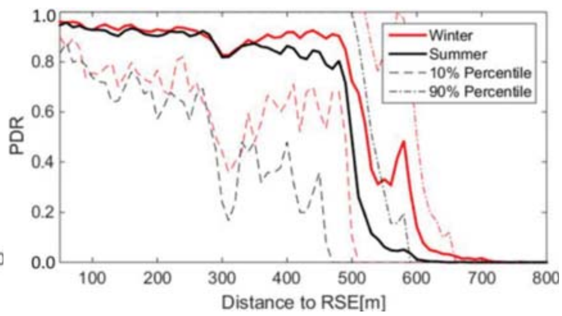
(a) PDR Variation in Day and Night Times [6]



(b) PDR Variation in Incoming and Outgoing Scenarios [6]



(c) PDR Variation in Rainy, Snowy and Sunny Weather Conditions [6]



(d) PDR Variation in Winter and Summer [6]

Fig. 2.11: Observations in [6]

Finally, the paper concludes that the communication system operates poorly in Non-Line-of-Sight (NLOS) situation.

In another experiment by M.E. Renda et al [36] an evaluation of Packet Inter-arrival Time (PIT) in IEEE 802.11p vehicular ad-hock networks (VANETs) is carried out. The experiment is on a V2V scenario and they collect information on PDR, PIT, and PIT blackouts. Any $PIT > 1s$ is considered a blackout. They arrive at the conclusion that PIT blackouts are a very important measure of a V2X communication system. Also, since a predicted PIT using an average PDR will lose such information, the latter alone will not be enough to asses a V2X communication system.

2.2.1.3 Wireless Fidelity (Wi-Fi)

Wi-Fi is part of the broader family of standards defined by the IEEE 802.11 standard, of which DSRC (IEEE 802.11p) is one member. The family has several standards as illustrated in Table 2.3 [7],

In general, Wi-Fi consists of 11 overlapping channels (Fig. 2.12). However, in

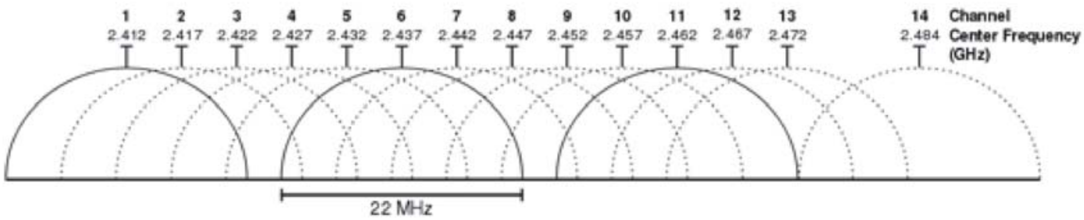


Fig. 2.12: Wi-Fi Spectrum [7]

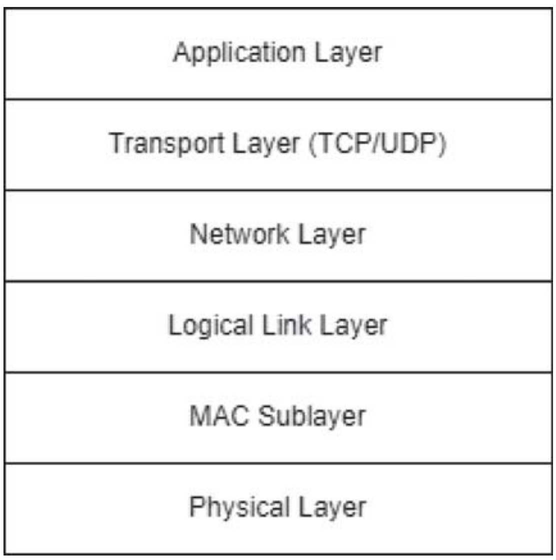


Fig. 2.13: Wi-Fi Protocol Stack

TABLE 2.3: Wi-Fi Generations[7]

Generation	Adopted	Year	Frequency
IEEE 802.11	(Wi-Fi 0)	1997	2.4 GHz
IEEE 802.11 b	(Wi-Fi 1)	1999	2.4 GHz
IEEE 802.11 a	(Wi-Fi 2)	1999	5 GHz
IEEE 802.11 g	(Wi-Fi 3)	2003	2.4 GHz
IEEE 802.11 n	(Wi-Fi 4)	2009	2.4/5 GHz
IEEE 802.11 ac	(Wi-Fi 5)	2013	5 GHz
IEEE 802.11 ax	(Wi-Fi 6)	2021	2.4/5 GHz
IEEE 802.11 ax	(Wi-Fi 6E)	2021	6 GHz

some regions, this could be 13 or 14 channels. Also, as mentioned in the Table 2.3, Wi-Fi utilizes 2.4 GHz, 5 GHz and 6 GHz frequency bands. Also, Wi-Fi has transmission rates from 1Mb/s – 9608Mb/s in distances 100m - 250m outdoors, depending on the generation.

The Wi-Fi protocol stack is comparatively simpler (Fig. 2.13) and the vanilla Wi-Fi does not have WSMP capability. However, it has TCP and UDP communication capabilities. Wi-Fi devices also have a defined set of message types, Management, Control, Data and Extension. These frames can be modified according to user requirements which enables this research project. In particular, Wi-Fi Beacons (W-Beacons) have been used for a variety of novel applications as presented later in this Chapter.

2.2.1.4 Wi-Fi Based Experiments

Nguyen et al [37] present an implementation of a low-cost Wi-Fi-based communication system focusing on V2V and V2I communications for low-speed vehicles such as motorbikes, bicycles, etc. This implementation attempts to solve the high cost point of DSRC communication systems. Authors have used ESP32 devices with ESP-NOW communication architecture for direct V2V communications and ESP-MESH architecture for multi-hop communications. Moreover, they mention creating a network among RSUs using General Packet Radio Service (GPRS). Fig. 2.14 depicts this communication architecture.

The authors have successfully developed a collision detection and warning system using a sonar-based ranging sensor and an accelerometer. Furthermore, the authors use the following as performance metrics of their system.

- Max speed for V2V communication
- Max range for V2V communication
- Max speed for V2I communication
- Max range for V2I communication

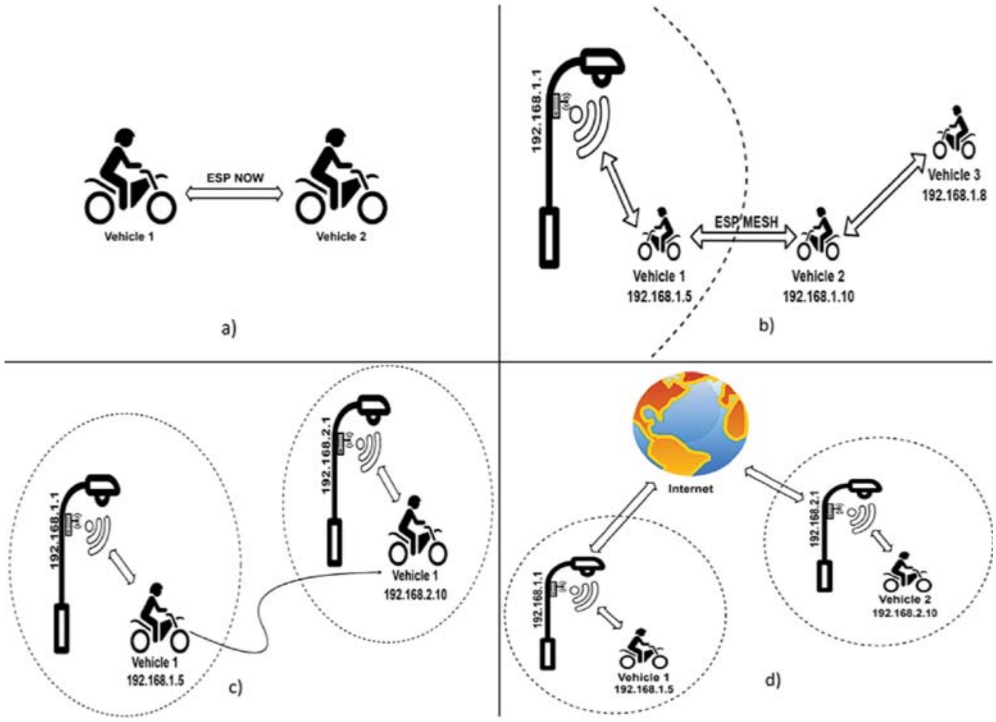


Fig. 2.14: Wi-Fi Protocol Stack

Authors of [8] develop and evaluate a Vehicle-2-Bicycle (V2B) communication system using 2.4GHz IEEE 802.11 b/g technology. Both the beaconing and continuous transmission scenarios are considered in the study. The system is evaluated using Commercial Off-The-Shelf (COTS) equipment to measure the Received Signal Strength Indicator (RSSI), throughput, and PIT as performance metrics. PIT is defined as the time interval between consecutive successfully received beacons. Two scenarios of the bicycle approaching/departing a vehicle, as shown in Fig. 2.15 are considered in the study. RSSI, throughput, negotiated data-rates, and PIT values are measured and calculated in the said scenarios as shown in Fig. 2.16.

Wi-Fi has also been used in heterogeneous architectures. Authors of [9] use 4G and Wi-Fi (IEEE 802.11b) in a simulation to create a heterogeneous architecture to be

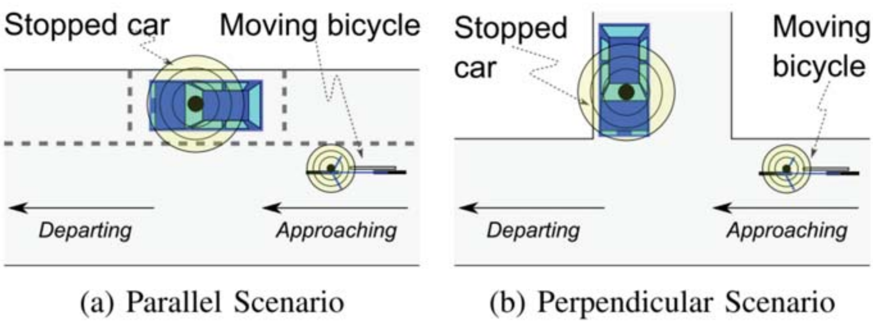
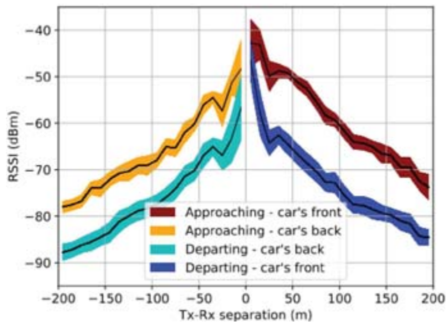
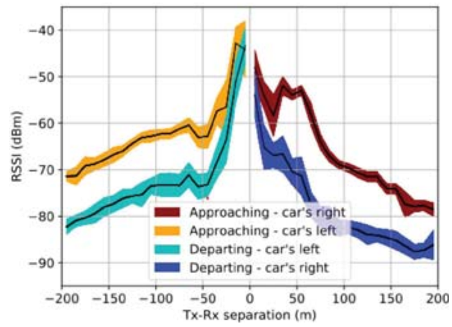


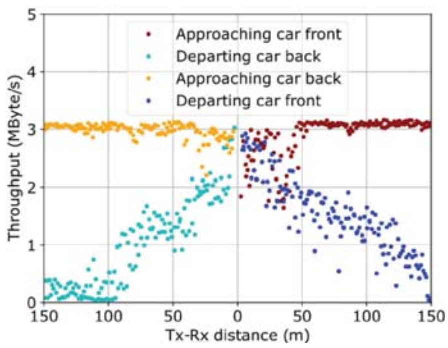
Fig. 2.15: Considered Scenarios [8]



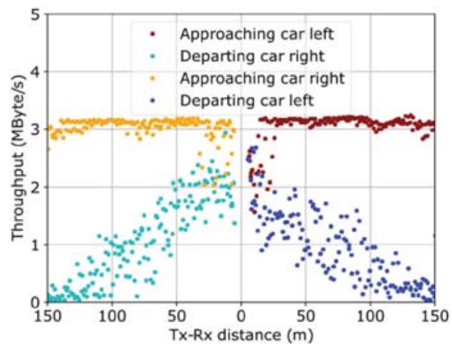
(a) RSSI Variation in Parallel Scenario [8]



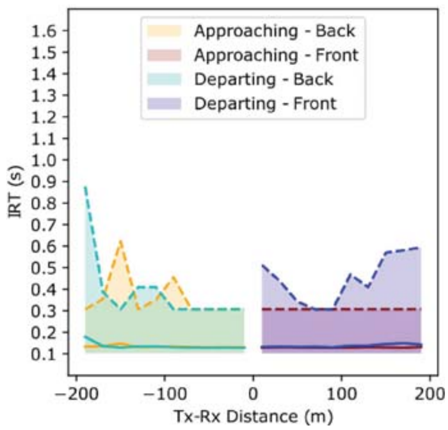
(b) RSSI Variation in Perpendicular Scenario [8]



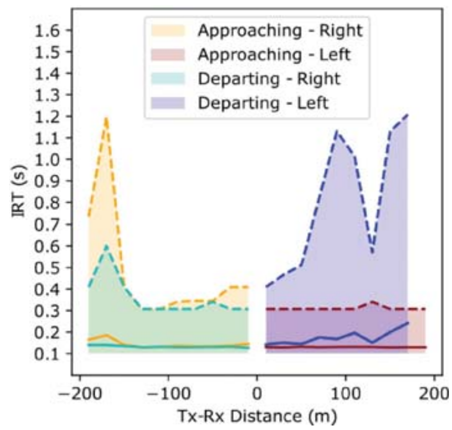
(c) Throughput Variation in Parallel Scenario [8]



(d) Throughput Variation in Perpendicular Scenario [8]



(e) PIT Variation in Parallel Scenario [8]



(f) PIT Variation in Parallel Scenario [8]

Fig. 2.16: Observations in [6].

used in Intersection Collision Avoidance (ICA) systems as shown in Fig. 2.17. This system uses W-Beacons to create clusters in each road leading to the intersection. An appointed cluster head will use 4G to communicate with a base station at the intersection. The cluster head will forward the information received from the base station to the cluster using W-Beacons. Finally, the authors evaluate the performance of this system in 3 configurations.

- Wi-Fi only.

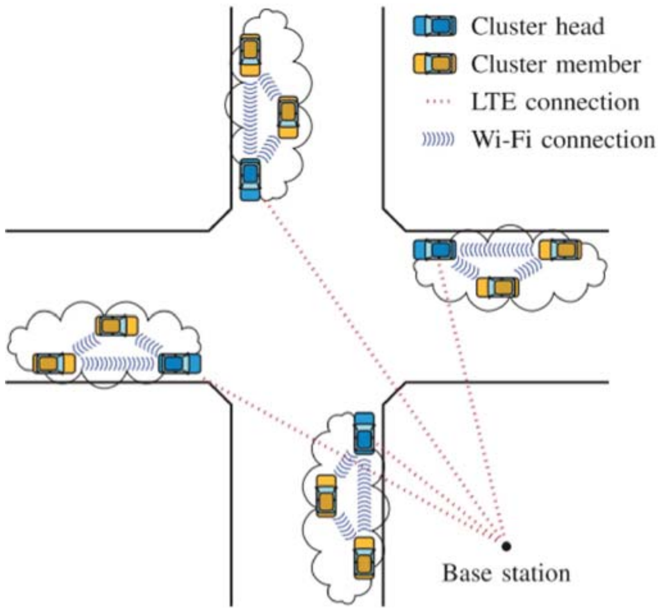
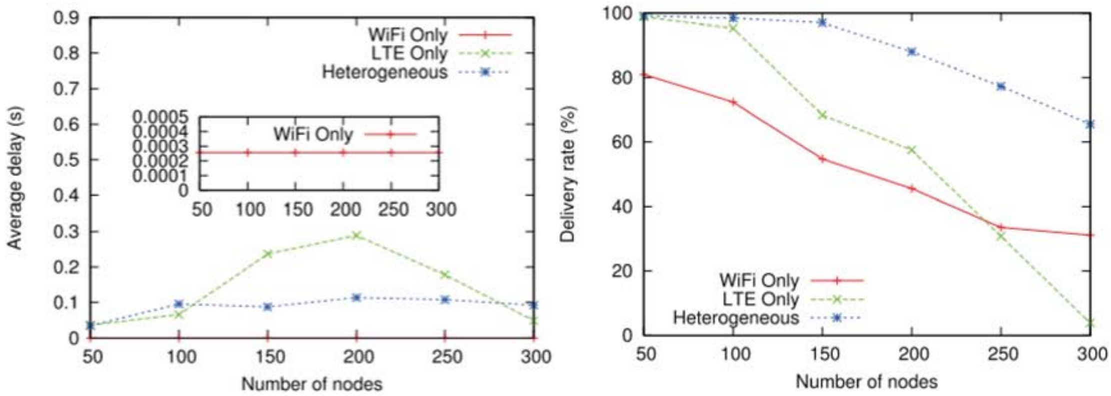


Fig. 2.17: Cluster Based ICA Communication Architecture [9]



(a) Average Delay Vs Number of Nodes [9]
(b) Average PDR Vs Number of Nodes [9]

Fig. 2.18: Observations in [9]

- LTE only.
- Heterogeneous.

Packet delay and PDR have been used as the performance metrics of the evaluation. The results as in Fig. 2.18, shows that from the considered scenarios, Wi-Fi only system has the lowest packet delay. However, it also has the lowest PDR. Also, the considered heterogeneous system demonstrates good packet delay statistics and excellent PDR performance.

Ideas and experiments have been reported using UDP messages with Wi-Fi for V2X communications, such as [38]. However, the performance of this usage of socket communication in V2X scenarios is below expectations since it requires an authenticated connection between the devices, which takes a significant time to establish.

2.2.1.5 DSRC vs Wi-Fi

DSRC and Wi-Fi both share the same IEEE 802.11 base protocol set. Therefore, they share many similarities. However, Wi-Fi is not purpose-built for communications in high-speed outdoor vehicular environments. Also, DSRC has removed the setup steps of IEEE 802.11, including authentication, before commencing communications with its Outside the Context of the Basic Service Set (OCB) mode [3] to reduce the packet delays, which are present when using Wi-Fi. In many countries, authorities have put up regulations, and regulatory restrictions are placed for transmitting power in both Wi-Fi and DSRC. However, DSRC is allowed 10dB higher transmit power compared to Wi-Fi.

However, some aspects of DSRC can be mimicked using W-Beacons. The intended use of W-Beacons is to announce the availability of an access point(AP) to the prospective clients in the vicinity. These carry information such as the Service Set Identifier (SSID), data-rate capabilities, etc. Most importantly, W-Beacons are broadcast before the connection setup process. This similarity to the OCB-mode of operation of DSRC may be exploited to mimic WSMP messages.

The standard format of W-Beacons is shown in Fig. 2.19. This message contains a few user-configurable fields, such as SSID and Vendor Specific Information Element (Vendor IE). While the SSID element can carry 32bytes of information, the Vendor IE can carry up to 255bytes of data. These can be used to mimic the DSRC messages.

2.2.1.6 Inferences

Numerous studies have been conducted on developing DSRC alternatives or dual communication systems to be used in V2X communications, [8], [9], [4], [5], etc. With the development of joint communication systems, the number of vehicles participating in ITS applications can be improved significantly. This is because many technologies being able to provide V2X facilities reduce the monopolistic nature of DSRC, and many vehicle manufacturers will be able to include V2X communication devices in their low-tier vehicles.

Since the purpose of this research is to improve the ITS application usage in de-

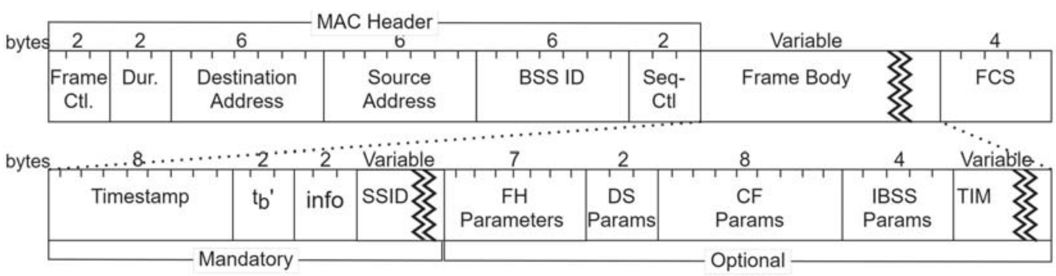


Fig. 2.19: Standard IEEE 802.11b Beacon Frame

veloping economies, it was decided to research the feasibility of using IEEE 802.11b Wi-Fi technology for I2V communications. Unlike DSRC, there are many manufacturers of IEEE 802.11b-enabled devices. Hence, COTS IEEE 802.11b-enabled devices are abundant and more economical than DSRC-enabled COTS devices.

However, since there are vehicles that are already equipped with DSRC-enabled devices, it was decided to design the system so that it will be able to coexist with such DSRC infrastructure. Therefore, the research was focused on developing an integrated DSRC / Wi-Fi communication system.

There are many performance metrics used in the literature. From these, PDR, PIT, MR, ER, and the probability of situation awareness blackouts were chosen as performance metrics to evaluate the joint communication system. Since this system will not be used for data streaming applications, metrics such as throughput and data rates will not be considered.

2.2.2 Hardware Platforms

With the recent developments in MCUs and processing units, there is a variety of candidate hardware platforms. Also, many companies have developed SoC that comes equipped with different communication technologies. This has made the system designs less complex and less expensive.

2.2.2.1 Custom Solutions

It is possible to implement a communication system from scratch by designing an embedded system with communication capabilities and a processing unit. Zehn et al develop such an embedded system with a DSRC interface in their study [39]. An STM8L151G Microcontroller Unit (MCU) was used as the processing unit. As for the Radio Frequency (RF) chip, BK5823, SKY6605 and TC32168FTG have been experimented with. The system design is as shown in Fig. 2.20. Universal Asynchronous Receiver-Transmitter (UART) and Serial Peripheral Interface (SPI) are used for the communication between a computer and the RF chip.

Using this method, another RF interface can be included to enable the Wi-Fi communications

This implementation allows for designing of systems with very specific capabilities. However, it is complicated and could become an expensive process than using a COTS device.

2.2.2.2 Single-Board Computer (SBC)

Since the last few decades, the market for miniaturized computers has expanded. Recently, they have been able to include all the components into a single Printed Circuit

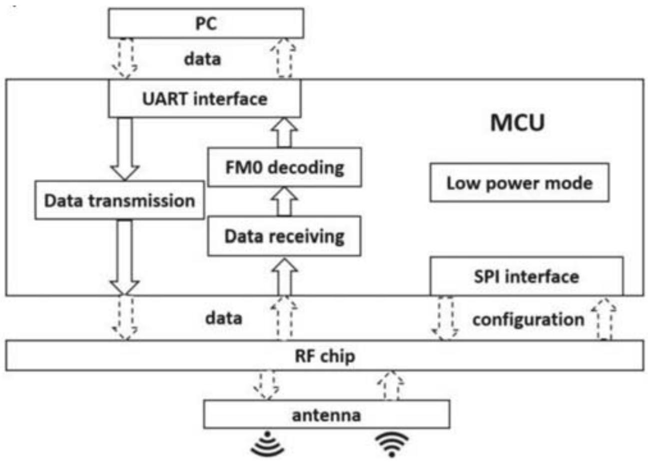


Fig. 2.20: Embedded System Design

Board (PCB), which are then named SBC [40], [41], [42]. Most of these devices are equipped with many communication interfaces such as Ethernet, Wi-Fi, Universal Serial Bus (USB), UART, Inter-Integrated Circuit (I^2C), etc., and these SBCs have superior capabilities. Therefore, these in conjunction with an RF device, can be used to implement a DSRC / Wi-Fi joint communication device.

Experiments done in [36] and [43] use such devices that have been built using an RF interface and a Linux machine / SBC. In [8], the authors use COTS standard-compliant radios connected to a laptop for their measurements. This could easily be replaced by an SBC. In [44], the authors have reconfigured SparkLAN WPEA-128N devices, which are IEEE 802.11a/b/g/n devices for DSRC frequency. The drivers have been configured into a DSRC stack and connected to a Gateworks Ventana GW5400 SBC to develop a DSRC device that is capable of being used in V2X communications. DSRC device manufacturers also tend to use this method to develop their devices [45].

2.2.2.3 SoC Devices

SoCs themselves can be considered as embedded systems. They are built around either an MCU or a microprocessor. A comparison between an SoC and an MCU is shown in Table 2.4. As evident by the comparison, these devices are more capable than an MCU and have a host of peripherals. Hence, they can be interfaced with a lot more sensors than an MCU. However, these capabilities come at a higher price than an MCU's. Also, these devices don't have as much processing capacity as an SBC. As such, they won't be able to process complex algorithms like an SBC.

2.2.2.4 Inferences

SoCs can be considered as a compromise between custom solutions and SBC-based solutions. SoCs allow the developer to use many communication interfaces, such as

TABLE 2.4: Comparison Between SoC and MCU.

SoC	**MCU**
Specific peripherals	Less specific general-purpose peripherals
High number of peripherals included	Less number of peripherals included
More expensive	Cheap
Higher memory(up to GB scale)	Small memory (KB scale)
Usually has an operating system	No operating systems
e.g.: PIC devices,Intel 8051, Atmel MCUs,	e.g: ARM processors, ESP32, Qualcom Snapdragon processors

in SBC devices. Also, these devices have more processing power than an MCU but less than an SBC. However, these devices have not been mentioned in the literature for use in V2X communications. Comparison between MCU, SBC, and SoC is shown in Table 2.5.

TABLE 2.5: Comparison Between SoC and MCU.

Quality	**MCU**	**SBC**	**SoC**
Complexity	High	Low	Low
Processing power	Low	High	Moderate
Cost	High	Low	Moderate
IEEE 802.11p capabilities	Have to add an RF chip to enable IEEE 802.11p	Have to add an IEEE 802.11b interface and reconfigure it for IEEE 802.11p	Have to add an IEEE 802.11p communication interface separately
IEEE 802.11b capabilities	Have to add an RF chip to enable IEEE 802.11b	Already comes with an IEEE 802.11b interface	Comes with an IEEE 802.11b interface in some cases

Designing an embedded system from ground up with an MCU is complicated. On top of that, developing one with two RF interfaces makes it more complex with the need to handle RF interferences. Therefore, it was decided to purchase COTS devices for the development. However, IEEE 802.11b and IEEE 802.11p-enabled devices were not available. Hence, two devices were chosen. The IEEE 802.11p-enabled devices were from CohdaWireless [45],[46], and for IEEE 802.11b, the ESP32 [47] SoC was chosen.

2.2.3 Security and Encryption

Security is a vital aspect of any communication system, and its significance increases as the risk levels of the application increase. the authors of [48] have conducted a comprehensive survey on security measures used in the VANET field. Identified design goals can be categorized into

- Security Requirements.
- Privacy Requirements.

A Few important factors have been identified under these goals and shown in Fig. 2.21.

- Entity Authentication: Verification of the sender's legitimacy.
- Message Authentication: Check and detect the integrity of the messages.
- Non-repudiation: Sender's inability to deny the authorship of a sent message.
- Traceability: Senders and receivers should remain anonymous to each other, while a central authority is able to uniquely identify each device in the system.
- Low overhead: Usage of low computational resources.
- Preservation of privacy: Senders and receivers should not be able to be identified by the messages sent by any other participants of the system.
- Unlinkability: Senders and receivers should be untrackable to other participants using their messages
- Unobservability: Sender's ability to broadcast messages, without being observed by third parties.

The system that is being developed in this research will be a broadcasting system. Some techniques found in literature, to be relevant in this context, are:

1. Packet Leash [49]: Temporal or geographical leash. Packets are disregarded if they exceed some threshold regarding distance or time.
2. Shared Key Distribution Using Encrypted Transmissions [49]: Before transmission, a shared key is transmitted to receivers using the RSA techniques.
3. Time Varying Keys [50]: Message is divided into blocks. First block is encrypted with a seed key K0. Then a pseudo-random number is XORed with the K0 to get K1, which is used to encrypt the second block, and so on.

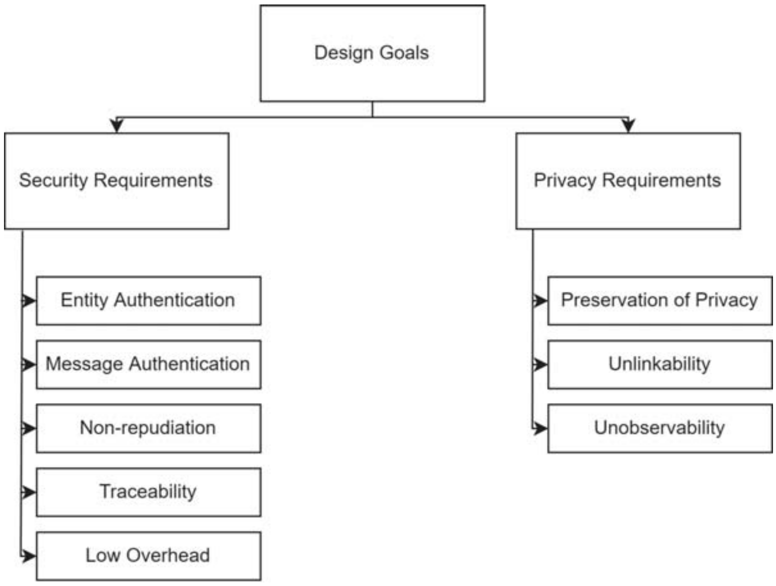


Fig. 2.21: Design Goals

4. Digital Signatures [51]: Digitally signing messages by a signature issued by an authority/manufacturer.

DSRC uses an Elliptic Curve Integrated Encryption Scheme (ECIES) to encrypt using an Advanced Encryption Standard (AES) key and transmit it to the receivers in the vicinity. Afterwards, the sender encrypts its messages using the AES key, which makes it quick and efficient. It also digitally signs its messages using a 125-byte-long signature.

2.2.3.1 Inferences

For the proposed system, a Pre-Shared Key (PSK), AES-based encryption was favored over an asymmetric encryption method to reduce the computational resources required. Therefore, sharing the key with an encrypted transmission technique was chosen to be implemented on the system.

2.3 System Modelling

The purpose of developing a system model is so that a user can evaluate the feasibility of the system to be used in a specific application. The two prominent methods can be found that have been used for modelling such systems:

- Mathematical and statistical modelling.
- Artificial Neural Networks (ANN).

In the recent literature, ANNs are found prominently being used for system modelling instead of mathematical techniques ([52], [53]). In [54], authors attempt to develop a propagation loss prediction model in an urban communication environment. They experiment with Walfiesh-Bertoni model, Hata model, conventional log distance shadowing model and a multilayer perceptron neural network model to develop the said model. It is observed that, even though the mathematical models can output a good approximation of the system, neural networks perform far better than a mathematical model.

2.3.1 Mathematical and Statistical Modelling

Conventionally, performance of a communication system can be modelled using mathematical techniques. Few such models are,

- Free space path loss
- Two-ray ground reflection
- Two-ray interference
- Rician fading
- Log-normal shadowing

Such a model can be developed by collecting data and fitting a curve onto the data points. Authors of [55] develops such model to model the signal propagation in a forest environment at the tree trunk level. A log normal model has been fitted to the collected data set using least square method. This new model has been compared with the ones in the literature and proven to be more accurate by comparing it with the collected data.

2.3.2 Neural Networks

Neural networks is an approximation of the functioning of the human brain. These include a set of neurons that work towards recognizing the relationships among the fed data. In the recent years, neural networks have become popular in propagation modelling, path loss prediction ([56]), channel estimation ([57],[58]), etc. Over the years, many neural network configurations have been developed through research. These can be divided into three sectors, which are,

- Multi-Layer Perceptron (MLP).
- Convolutional Neural Networks (CNN).
- Recurrent Neural Networks (RNN).

2.3.2.1 Multi-Layer Perceptron (MLP)

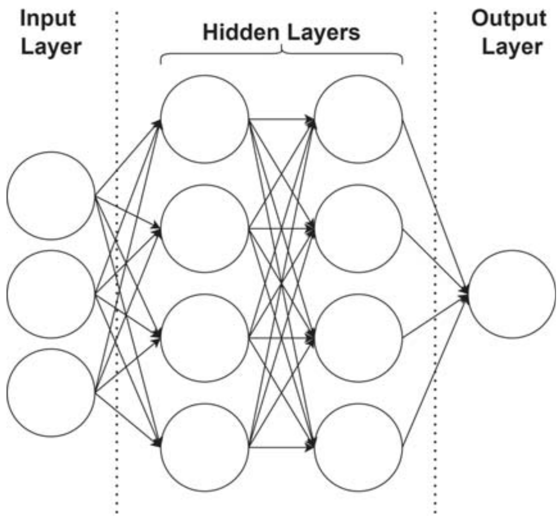


Fig. 2.22: MLP

As shown in Fig. 2.22, MLPs have a minimum of three layers, namely, input layer, hidden layer and an output layer. Having more than one hidden layer will make it a deep neural network. These can be highly effective in prediction, regression or classification problems. There have been a few researches in the literature, that uses MLPs in vehicular environments.

One techniques that has been observed commonly in the literature is, using neural networks to predict the error between a measured signal strength and a value predicted by a mathematical model such as COST 231 Walfisch Ikegami in [56].

2.3.2.2 Convolutional Neural Networks (CNN)

By design CNNs map two dimensional inputs into an output. They are able to find spatial relationships within the fed data. Therefore, these are primarily used for image classification and machine vision scenarios. However, the authors of [58] use a combination of a CNN and RNN in a channel estimation application. As shown in Fig. 2.23, their model consist of the four stages,

- 1 dimensional CNN
- 1 dimensional maxpooling layer
- Lon-Short Term Memory Cells(LSTM)
- Fully Connected Neural Network(FCNN)

They use the CNN's ability to extract and expose the features from a data set to extract features from the pilot sequence of the transmitter. Then the dimensionality of the extracted feature set is reduced by the maxpooling layer. After the data is fed to two LSTM networks for forward and backward predictions, it is sent through a FCNN to extract the channel frequency response.

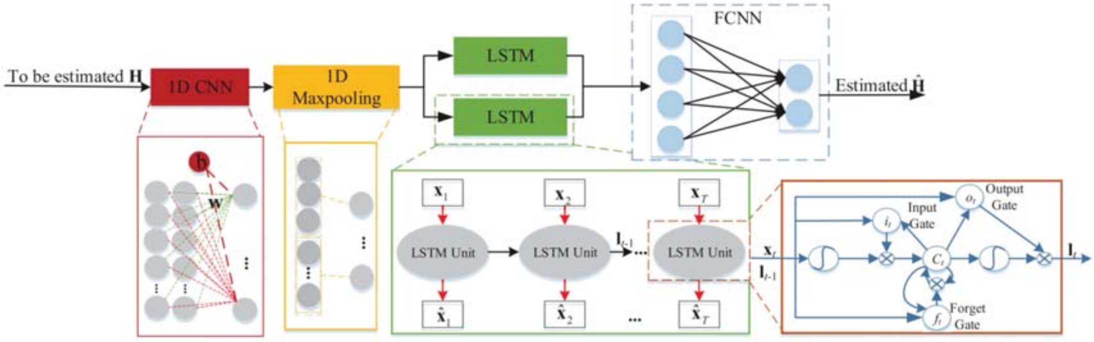


Fig. 2.23: ChanEstNet

LSTMs are a type of RNNs and are described in the next section.

2.3.2.3 Recurrent Neural Networks (RNN)

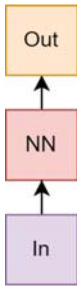
RNNs differ from both CNNs and MLPs. They are highly capable of finding temporal relationships among the data fed to the network. These are mainly used in cases where there are sequential data such as sentences, stock values, videos, etc. According to the arrangement of input and outputs to and from the networks, RNNs have four main categories which are shown in Fig. 2.24. As shown in the Fig. 2.24, the a state of the cell at the current iteration is taken forward to the next iteration. This is the reason why RNNs are said to have memory.

Over the years, researchers developed the LSTM networks. These have a longer short-term memory than the generic RNNs. Unlike generic RNNs, LSTMs are more immune to exploding or vanishing gradient issues.

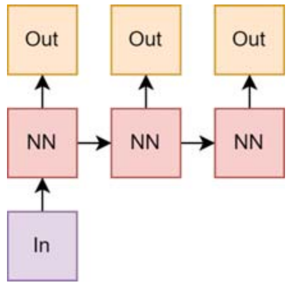
A. Long Short-Term Memory (LSTM)

   As shown in Fig. 2.25, an LSTM cell has a forget gate, input gate and an output gate, through which the data intake, process and cell state memory is controlled. Each gate has parameters which will be tuned in the training phase. LSTMs have been used in [59] to predict signal to noise ratio using 20 previous readings. These have also been used by the authors of [60] to predict channel state information (CSI) and RSSI values in a vehicular communication environment.

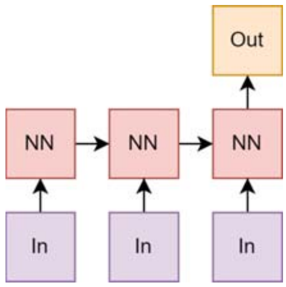
B. Bi-directional LSTM (Bi-LSTM)



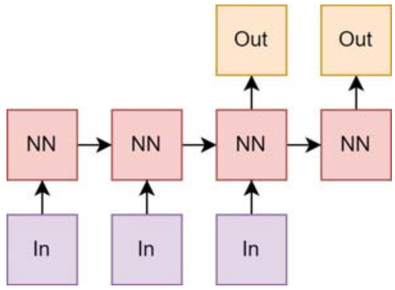
(a) RNN one-to-one



(b) RNN one-to-many



(c) RNN many-to-one



(d) RNN many-to-many

Fig. 2.24: RNN Configurations

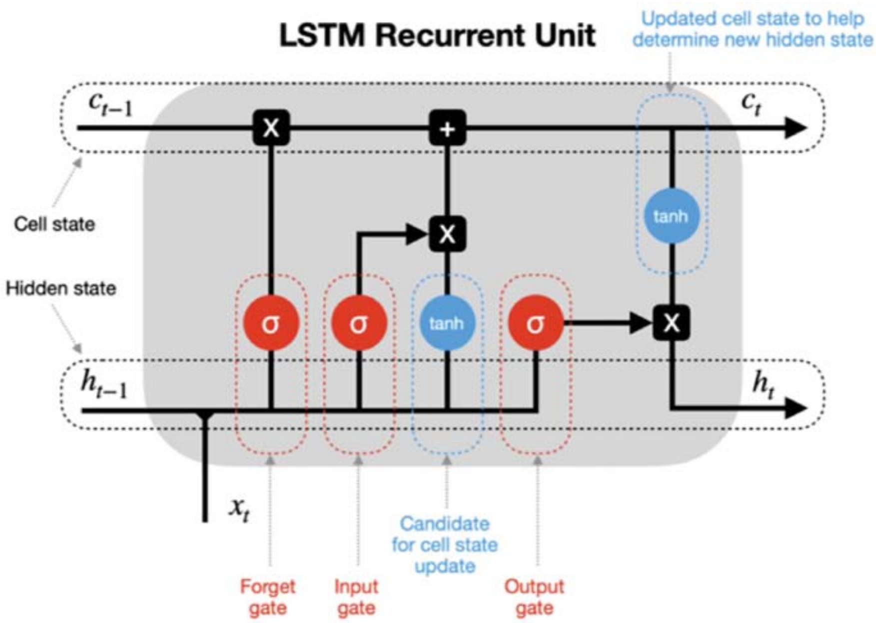


Fig. 2.25: LSTM Cell [10]

As depicted by Fig. 2.26, Bi-LSTMs have two layers of LSTM cells, which are operated independently. One of these layers travels forward on the provided data set, while the other layer travels backward. Therefore, these can utilize data from both sides of the prediction time step. These networks are predominantly used in natural language processing problems. However, the Authors of [58] and [61] use them in channel estimation tasks.

2.3.2.4 Model Evaluation

Once the model has been built, its accuracy must be evaluated. The authors of [62] investigate a Gated Recurrent Unit (GRU) based RNN to predict inter-arrival times of Cooperative Awareness Messages in 5G-based V2X sidelink communications. They have used MSE to evaluate the performance of their model. Furthermore, [63] goes through a development of multiple ANNs to predict path-loss in vehicular communications. The paper uses the following metrics to evaluate the performance of each model.

- MSE
- RMSE
- MAE
- R^2

2.3.2.5 Inferences

As described above, the current trend for developing system models is to use neural networks ([64], [65][66], [67], [68], [69], [70]) instead of mathematical techniques. Therefore, the model for the proposed system will be developed using a neural network. Since the system will be operating in a dynamic environment and the data will have significant temporal relationships among themselves, Bi-LSTM design was chosen for the model and MSE, RMSE, and R^2 will be used for evaluating the performance of the model.

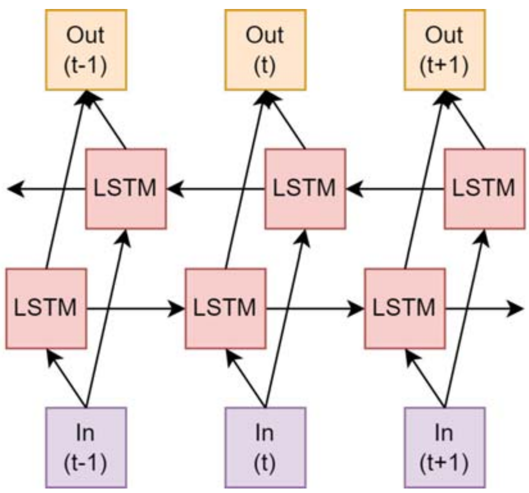


Fig. 2.26: Bi-LSTM.

CHAPTER 3

COMMUNICATION SYSTEM DESIGN AND IMPLEMENTATION

3.1 Introduction

The communicatino system that is developed through this research will be focusing the applications that are viable in low economic countries such as Sri Lanka. With the brief survey carried out to find the applications suitable for Sri Lanka, two main categories of applications were identified;

- Safety Applications.
  - Collision avoidance systems.
  - Blind spot warning systems.
  - Emergency vehicle transit.
  - Intersection control.
  - Hazard location warning.
  - etc.
- Infotainment Applications.
  - Lighting management.
  - Real-time parking management.
  - Advertising.
  - Electronic toll collection.
  - Variable speed limits.
  - Traffic management.
  - etc.

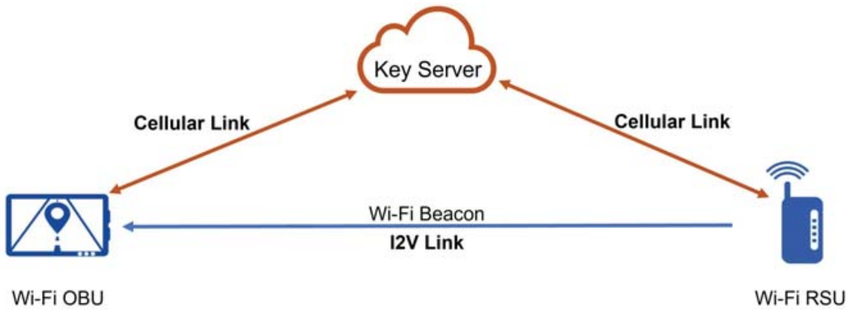
Among these applications, a subclass of ITS applications can be identified as *Active Road Signs* (ARS). This category focuses on bringing the road-signs to the interior of the vehicle to improve the information delivery to the drivers. These road signs can be,

- Static Road Signs - Bend ahead warning, Round-about ahead, etc.
- Semi-Dynamic Road Signs - Road work ahead warning, Hazard ahead warning, etc.

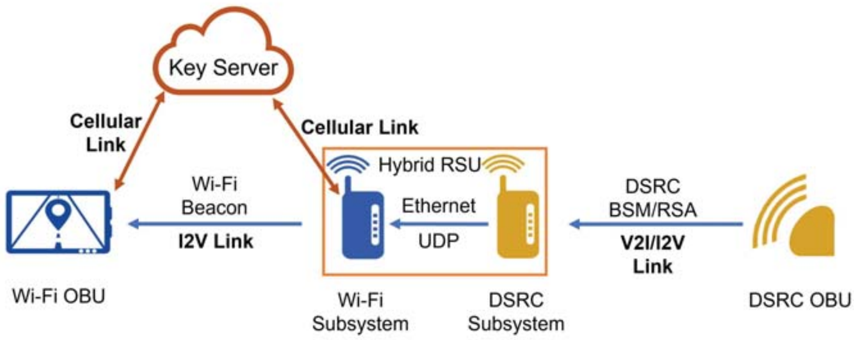
- Dynamic Road Signs - Intersection management color lights, Incoming railway vehicle warning, etc.

With the survey data, the ARS was selected as the application set to be catered by the communication system. Hence, the new communication system will be designed cater the required specifications for an ARS system.

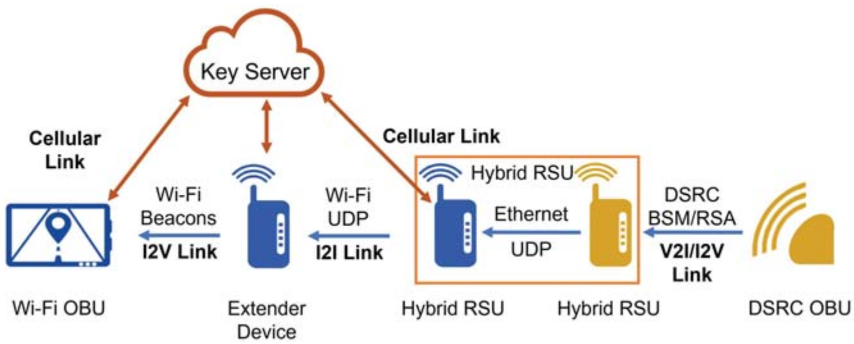
3.2 System architecture



(a) Wi-Fi Standalone Architecture



(b) Base Architecture



(c) Extended Architecture

Fig. 3.1: System Architecture.

Since this novel communication system is suppose to be an alternative for the

DSRC, communication technologies that have similar technologies was identified. 4G has been prominently used in literature as an alternative for DSRC ITSs. However, Wi-Fi and Bluetooth have operation modes that can be used to mimic the DSRC behaviours. From these three technologies, Wi-Fi was chosen as some research has been conducted on it being used in vehicular environments. Then, as mentioned in the literature review, the capabilities of the Wi-Fi-based system will be extended to support the coexistence with DSRC and support both communications.

At first, the Wi-Fi only system was designed as shown in the Fig. 3.1a.Then this was extended as mentioned earlier to be able to communicate with DSRC components as shown in the Fig. 3.1b. however, to overcome the low range of Wi-Fi, an extender device was designed and included into the architecture as shown in Fig. 3.1c.

3.2.0.1 Components and features

A couple of ideas were entertained while selecting the communication components. Especially the Wi-Fi component. As mentioned in literature, Wi-Fi has many generations. Some even operating in the same frequency range as DSRC. One idea was to develop the Wi-Fi component with such 5GHz ranged generation and give it the ability to receive and transmit DSRC messages. Second was to use IEEE 802.11b and mimic the DSRC packet transmissions. Since there are existing researches employing the first idea,the second was chosen for this research.

Both the DSRC and Wi-Fi devices was sourced from COTS products. The DSRC device came equipped with a linux based SBC which was capable of handling Ethernet communications. Therefore, the mesage transmission between the two main components, DSRC and Wi-Fi could be achieved through an Ethernet link.

As mentioned in the literature review, the security of the system messages will be implemented through *Shared Key Distribution Using Encrypted Transmissions* technique. Two options were considered to share the key with the devices.

- Text message based.
- Web server based.

Considering the delay of text message services, a web server implementation was selected for the key sharing purposes. Therefore, a GSM/GPRS component had to be included in the system to establish the communication with the web server.

In contrast, the system will consist of, DSRC transmitters, DSRC/Wi-Fi Hybrid Roadside Unit (H-RSU) and Wi-Fi On-Board Unit (W-OBU) devices. These H-RSUs will include one DSRC subsystem and one Wi-Fi subsystem. However, this Wi-Fi subsystem within the H-RSU will have the capability to operate as a standalone Wi-Fi RSU(W-RSU) device.

3.2.0.2 Communication links

The communication links of the system are shown in Fig. 3.9.

A. DSRC

The DSRC link is between a DSRC device and the H-RSU. This will enable V2I communication in the DSRC subsystem. In this link there will only be DSRC packets including Roadside Alert (RSA) messages and BSM messages.

B. Ethernet

As mentioned earlier, the Ethernet is used to connect the DSRC subsystem with the Wi-Fi subsystem. This is used to forward the messages received at the DSRC subsystem to the Wi-Fi subsystem. For this, UDP will be used instead of TCP to reduce the delay in message forwarding.

C. Wi-FI

The Wi-Fi subsystem is responsible for delivering messages to the drivers. It implements V2I communication by using customized W-Beacons (C-beacons).

In the Wi-Fi subsystem,

D. Cellular

The cellular link is leveraged to communicate with the key server. The W-OBU devices and the Wi-Fi subsystem of H-RSU devices will use the cellular link to communicate with the key server to request for an AES key periodically.

3.2.0.3 Hardware components and specifications.

For the DSRC component, COTS devices manufactured by Cohdawireless will be used [45], [46].

- 802.11p radio.
- 10MHz bandwidth.
- 3-27Mbps data rates.
- -99dBm receiver sensitivity.
- +22dBm maximum transmit power
- NXP i.MX6 800 MHz Dual Lite processor, 1GB RAM, 4GB flash.
- Linux for stack and application.

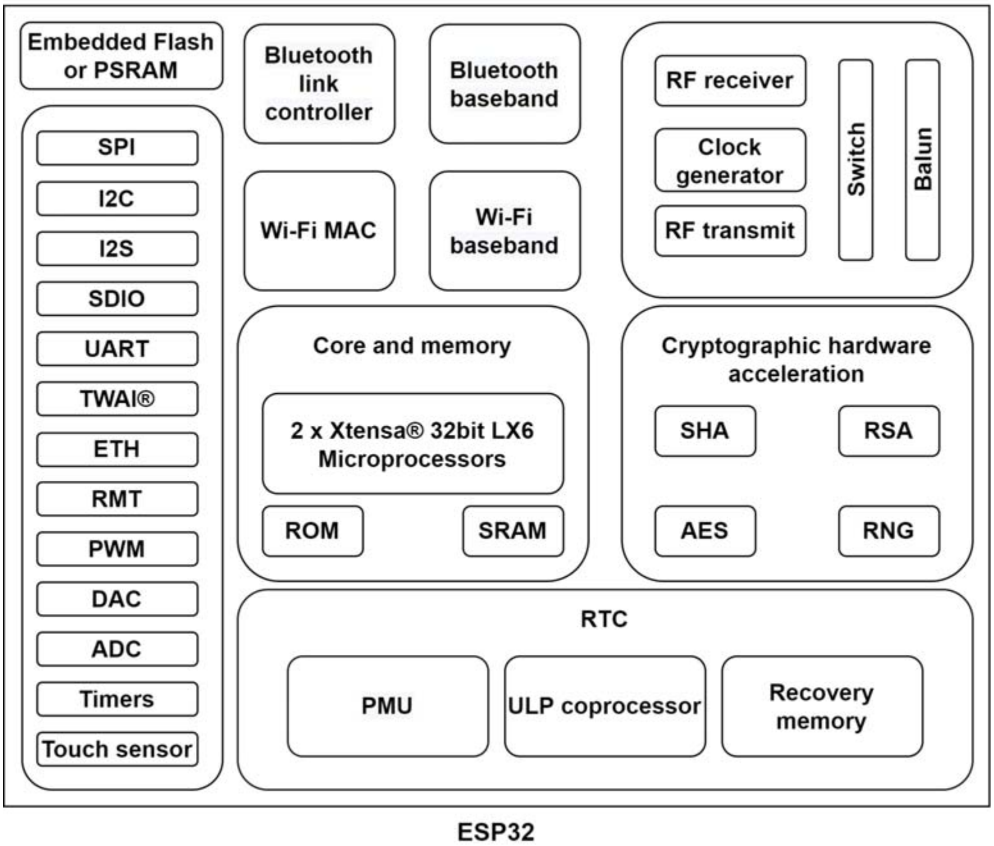


Fig. 3.2: ESP32 Functional Block Diagram

- 2.5m accurate GNSS receiver.
- Ethernet, USB, GPI, CAN.

For the Wi-Fi component, the ESP32-wroom-32s devices manufactured by Espressif systems was chosen. As shown by the Fig.3.2, these devices are equipped with a

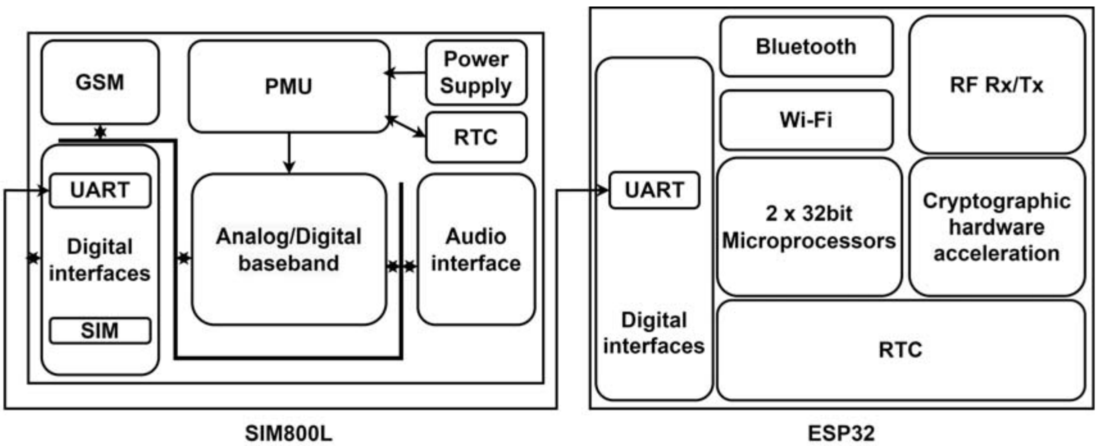


Fig. 3.3: ILYGO® TTGO T-Call V1.4 Functional Block Diagram

dual cor processing unit and various communication interfaces such as I2C, I2s, SPI, etc [71]. More capabilities of these are as follows

- 802.11b/g/n radio.
- Support for Station, SoftAP and Promiscuous modes.
- -98dBm receiver sensitivity.
- +20.5dBm maximum transmit power for IEEE 802.11b.
- Xtensa® dual-core 32-bit LX6 microprocessors, 520KB SRAM, 448KB ROM.
- 2.5m accurate GNSS receiver.
- ADC, I2C, I2S, UART, SPI, DAC, ADC,etc.

In the case of the H-RSU, an Ethernet module (W5500) was attached to the ESP32 device used for the Wi-Fi subsystem through the SPI port of the ESP32. For the ESP32 device used in W-OBU devices, the SPI port is connected to a LCD display. This display is used to convey information to the driver. In both cases these ESP32 devices are coupled with a 2.4GHz monopole antenna with a 3dBi gain.

Many third parties have developed various development boards/expansion boars using the ESP32 device. Since the system is to use a cellular link to connect to the key server, the LILYGO® TTGO T-Call V1.4[72] modules were chosen to develop the system. These devices comes equipped with SIM800L modules (Fig. 3.3), which are capable of handling GSM and 3G communications.

3.2.1 System implementation

For the ease of presenting and understanding, the system implementation will be divided into component-wise sections. There are 6 major components.

- DSRC V2I
- H-RSU Component
- Extender Component
- W-OBU Component
- W-RSU Component
- Key Server

3.2.1.1 DSRC V2I

DSRC V2I component considered in this section includes only the DSRC transmitter OBU. These DSRC transmitter devices fitted to vehicles are not customized and transmit default BSM packets, which includes information such as,

- Speed
- Location
- Heading
- Vehicle dimensions, etc

3.2.1.2 H-RSU Component

H-RSU component considered in this section includes the Wi-Fi and DSRC subsystems.

The DSRC receiver in the DSRC subsystem of the H-RSU, is however customized. It is programmed to generate UDP packets which include some data elements of received BSMs. These elements include and not limited to,

- Speed.
- Latitude.
- Longitude.
- Heading.

The structure of the UDP packets can be predefined depending on application requirements. These constructed packets are sent to a pre-programmed IP address using

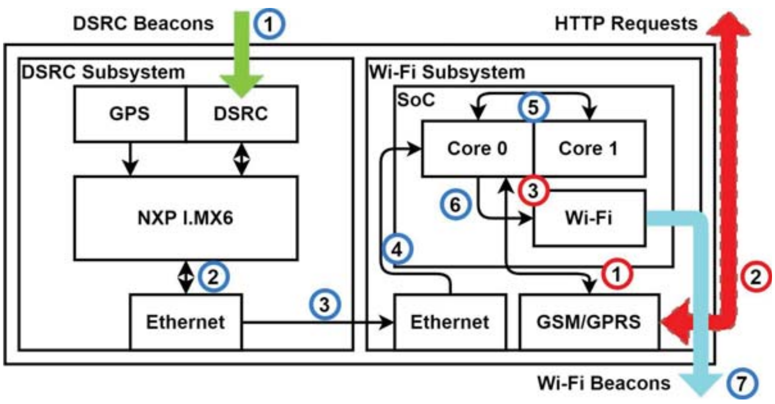


Fig. 3.4: Integrated RSU

the Ethernet port of the SBC inside the DSRC receiver unit. The stepwise process is shown in Fig. 3.4.

The LILYGO devices used for H-RSUs are fitted with an Ethernet module so that it can receive the UDP packets sent from the DSRC subsystem. The steps following the step 4 of Fig. 3.4, depends on the configuration of the deployed system. The device employs its two cores to improve the performance of the device.

- With Extender Unit:

  If the deployed system has an extender device, LILYGO unit will encrypt the received UDP packets and create Wi-Fi UDP packets. The ESP32 of the LILYGO device will host a secured AP to which the extender device will connect. Afterwards, these encrypted UDP Packets will be passed to the extender unit using the Wi-fi connection.

- Without Extender Unit:

  When the deployed system will not be having an extender device, the H-RSU's LILYGO device will produce C-Beacons which will be broadcast in the vicinity of the H-RSU.

There are a couple of important topics to be touched on, which will be mentioned in future sections also.

- Encryption

  This step is taken to ensure the security of the communication system. This is only implemented on the Wi-Fi section of the system. LILYGO devices use the GSM module to communicate with a remote server to request an encryption key. More details about this server will be discussed in *Key Server* section. This received key is used to encrypt and decrypt messages at LILYGO devices.

- C-Beacons

  Wi-Fi beacons are used in the novel system to broadcast information to drivers. Fig. 3.5 shows the default format and the format used in the novel system. These Wi-Fi beacons have various data fields some of which are mandatory and some optional. In the novel design, the *Vendor Information Element (VendorIE)* is being leveraged to send the data to drivers. This is an optional field which is used by various vendors to send vendor specific information embedded within the beacons. It can carry 256bytes of data. However, it has allocated a space for a 3 byte long Organizationally Unique Identifier(OUI). Hence the amount of data it can carry becomes 253bytes. The structure of this data packet is also pre-configured depending on application requirements.

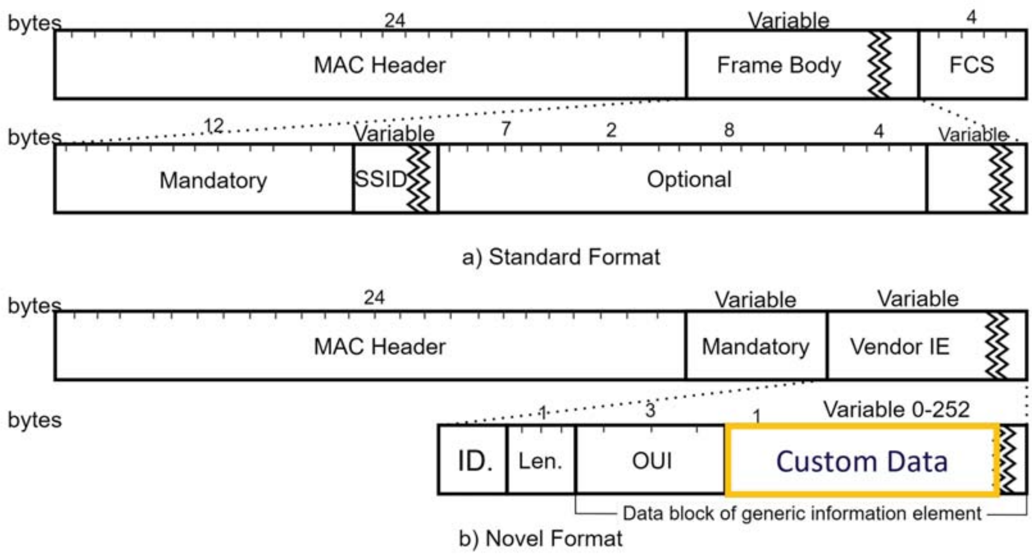


Fig. 3.5: C-Beacons

3.2.1.3 Extender Component

The transmit power of Wi-Fi is limited subject to statutory regulations, making the communication range very small compared to DSRC and C-V2X technologies. Therefore, the extender device is introduced to the system to overcome this issue. This As mentioned in the previous section, when the extender device is present in the system, the Wi-Fi subsystem of the H-RSU is set to enable an AP. This AP will be a password protected. Afterwards, it listens to the incoming UDP packets from the host. In such event, it will extract the data packet from the UDP packet and will form the C-Beacons. It will not process or decrypt the received packets before forming the C-Beacons. The process is shown by the Fig. 3.6. The device employs its two cores to improve the performance of the device.

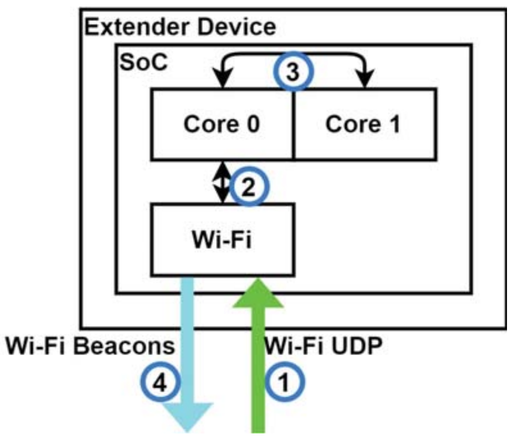


Fig. 3.6: Extender Device

3.2.1.4 W-OBU Component

W-OBU devices are equipped within the vehicles. These devices are responsible for delivering necessary information to the drivers. These devices are also built around the LILYGO devies and are also connected to the key server. These devices will also have the AES key used to encrypt data at H-RSU devices. When this device receives a C-Beacon, it will decrypt the message using this key. Then it will generate the necessary warnings to the driver. The process is shown by the Fig. 3.8. The device also employs its two cores to improve the performance of the device.

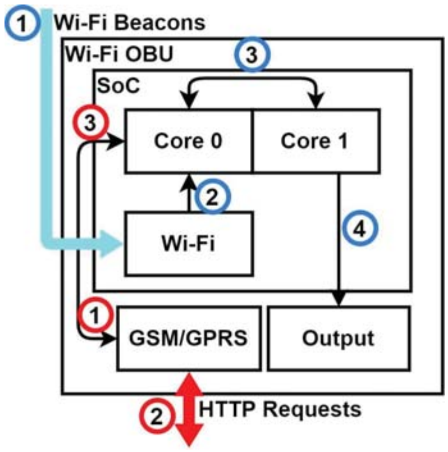


Fig. 3.7: W-OBU; Blue circles - packet reception process, Red circles - key retrieval process.

3.2.1.5 W-RSU Component

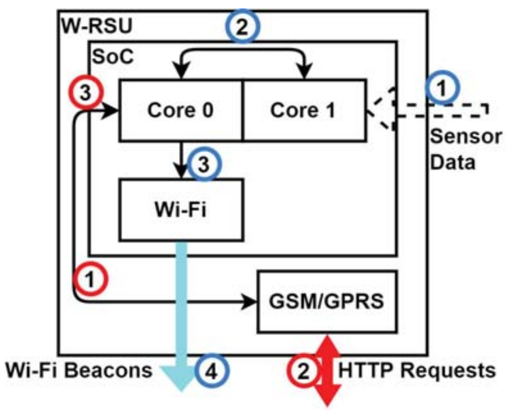


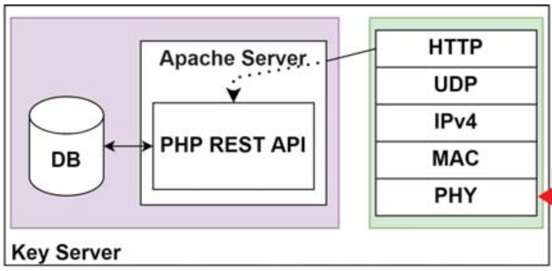
Fig. 3.8: W-RSU

These devices' functionality is similar to the function of an extender device. These devices will either be connected with a set of sensors to analyse data and generate

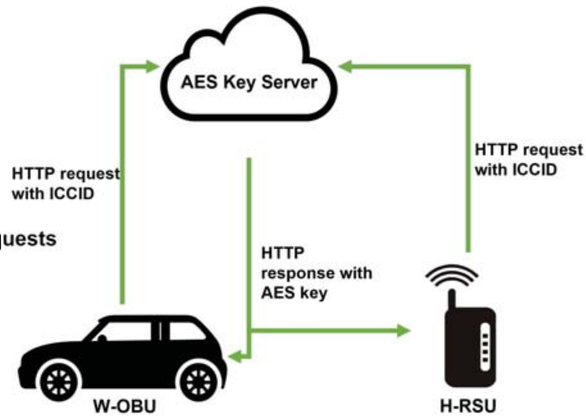
C-Beacons to transmit information or will be preconfigured to broad cast a set of information. In any case, it will encrypt the data to be broadcast with an AES key taken from the key server, with which it forms C-Beacons and broadcasts them.

3.2.1.6 Key Server

The Key Server was implemented on a remote server as a REST API. It includes a database, an Apache server and PHP scripts to enable functionality. The server database keeps records of all the LILYGO devices that have been deployed. These devices are equipped with a cellular sim card and the server uses the ICCID of these sim cards to uniquely identify each device. The server generates AES keys periodically. The devices are required to send their ICCID with the HTTP request to retrieve an AES key. When such request is received, the PHP REST API checks if the ICCID is recorded in the database, and if so, sends the AES key that is active in that period. The servers side process is displayed in the Fig. 3.9a and the key retrieval process is shown in Fig. 3.9b.



(a) Key Server



(b) Key Retrieval

Fig. 3.9: Key Server Implementation and Operation.

CHAPTER 4

EXPERIMENTAL EVALUATION

4.1 Introduction

An experimental evaluation of the novel system was selected as a research objective at the start of the project. However, before committing to a fully-pledged data collection followed by an analysis, a preliminary test and an analysis was carried out to identify the important variables and the system's maximum performance.

4.2 Preliminary test

4.2.1 Experiment

This test was conducted in the configurations shown in Table 4.1. Tests were conducted in the premises of the University of Moratuwa and the B295 road as shown in Fig.4.1.

For this test, ESP32 devices were used as the test was only on the packet transmission and reception. Like LILYGO devices, these ESP32 devices have an output power of 19.5 - 20.5dBm and a receiver sensitivity of -98dBm. It was also equipped with a 2.4GHz, 3dBi antenna for the experiment.

- Static Scenario

  Transmitter device was mounted on a stationary pole. The location of this device is recorded using the GPS sensor of a mobile phone with an accuracy of 3m. The receiver device was also mounted on a pole with a laptop attached to the device. At the start, this apparatus is placed close to the transmitter; 50m away from it. Then in every test iteration, the receiver apparatus is moved away from the transmitter; 40m at a time. When the test is being conducted, the transmitter is set to transmit for 120s. These are data packets of 36bytes including a GPS coordinate, speed value, heading value and a sequence number. After this time slot, the transmitter is turned off and the receiver apparatus is moved further away from the transmitter. This is repeated until the receiver stops receiving packets from the transmitter.

  As mentioned earlier, this test was conducted on the university premises and along the B295 road. First location simulated a low traffic scenario and the second location a moderate traffic scenario.

- Moving Scenario.

TABLE 4.1: Preliminary Test Configurations

Test ID	Name	Description
LS05_0	Low Traffic - Static Receiver (5ms).	Data collection in low traffic environment with 5ms beacon repetition interval.
LS50_0	Low Traffic - Static Receiver (50ms).	Data collection in low traffic environment with 50ms beacon repetition interval.
MS05_0	Moderate Traffic - Static Receiver (5ms).	Data collection in Moderate traffic environment with 5ms beacon repetition interval.
MS50_0	Moderate Traffic - Static Receiver (50ms).	Data collection in Moderate traffic environment with 50ms beacon repetition interval.
LM05_30	Low Traffic - Moving Receiver (5ms).	Data collection in low traffic environment with receiver speeds 30kmh^{-1} and 5ms beacon repetition interval
LM05_45	Low Traffic - Moving Receiver (5ms).	Data collection in low traffic environment with receiver speeds 45kmh^{-1} and 5ms beacon repetition interval

TABLE 4.2: Preliminary Test ID

L/M	S/M	5/50	_	30/45
Traffic condition	Receiver mobility	C-Beacon interval(ms)		Receiver speed(km/h)

The transmitter is placed as before. Then the receiver apparatus is setup on a Suzuki Swift 2017 RS car which has an acceleration of 10.52kmh^{-1}s^{-1} or 0-100kmh^{-1} in 9.5s. The W-OBU is placed behind the windshield. The CohdaWireless DSRC On-Board Unit (D-OBU) was used to record the location and speed information. This data was recorded every 100ms. This GPS antenna was mounted on top of the vehicle.

At the start of a test iteration, the vehicle would start from the furthest point on the road. This location does not receive packets from the transmitter. When the test iteration starts, the transmitter was turned on which was approximately 300m away from the vehicle's starting location. It transmits the same information as in the static scenario. Vehicle was given full throttle until it reached the desired speeds; which were 30 and 45kmh^{-1}. After reaching these speeds, it was maintained until the vehicle had passed the transmitter. The receiver apparatus

(a) Preliminary Test - Low Traffic Static Receiver

(b) Preliminary Test - Low Traffic Moving Receiver

(c) Preliminary Test - Medium Traffic Static Receiver

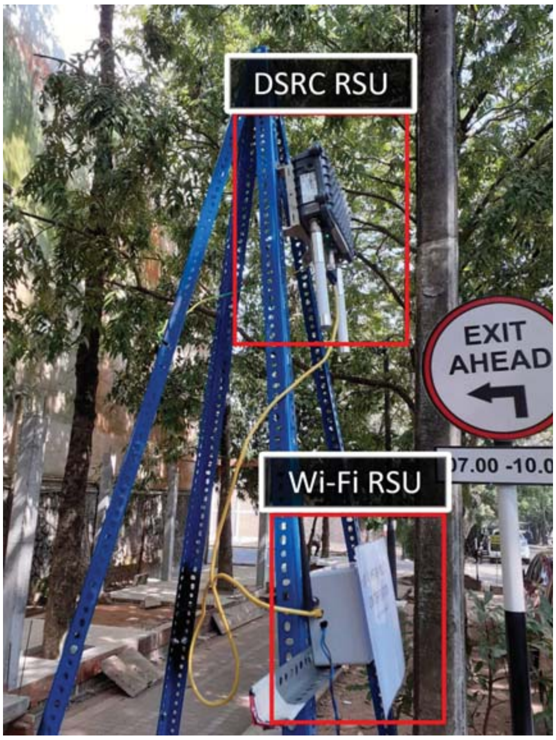
Fig. 4.1: Preliminary Test Scenarios.

was recording the packets and related information while the vehicle was moving towards the transmitter. The transmitter was shutdown as soon as the vehicle had passed it.

In all these scenarios, following data has been recorded.

- Respective receiver and transmitter coordinates.
- Time when a packet is received at the receiver.

(a) Vehicular Setup



(b) H-RSU Initial Test Setup

(c) W-RSU Test Setup

Fig. 4.2: Test Setup.

- RSSI of the received packet at the receiver.
- Sequence number of the received packet at the receiver.

Location is manually recorded in the static scenario. However, for the moving scenario, both GPS and receiver data are recorded on the same computer with time-stamped labels. These timestamps are used in the calculations to identify corresponding coordinate and packet groups.

Pictures of the first combined test unit, vehicle setup for the test and the W-RSU are shown in Fig. 4.2.

4.2.2 Calculations

All the data collected in the experiments were processed using MATLAB to have a better understanding of the system and to develop the final data collection campaign. The data of the static scenarios were used to understand the capability of the system. I.e. how the properties like range, packet loss and delay will behave with different transmission intervals and traffic conditions.

The data collected in the moving scenario was used to observe how the behaviour of the communication system changes when the receiver is moving at different speeds. Since the GPS location update interval was 100ms and the beacon transmission interval was 5ms, not every beacon has an associated GPS coordinate. Due to this reason and to reduce the multi-path propagation errors, the average of the beacons arrived in a 10m radius was taken as one reading. This is depicted in Fig. 4.3 for comprehensibility.

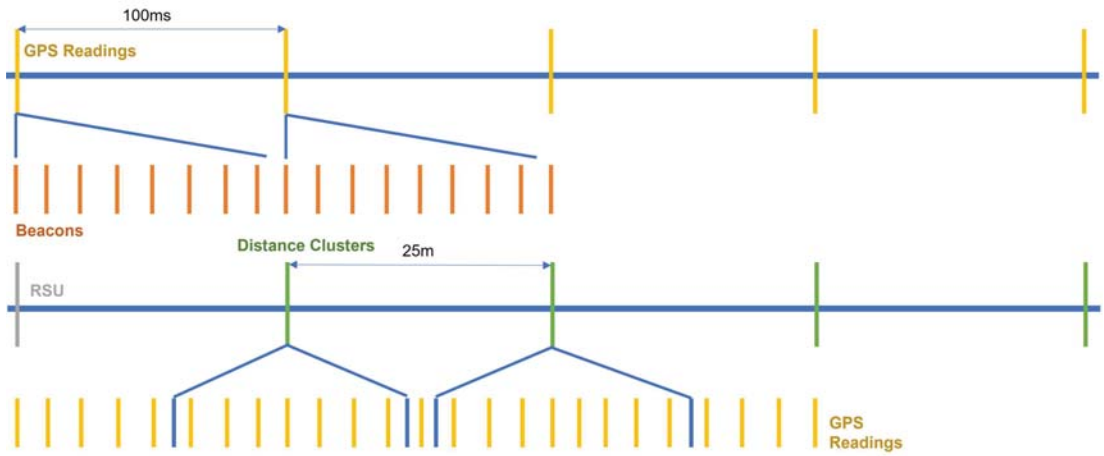
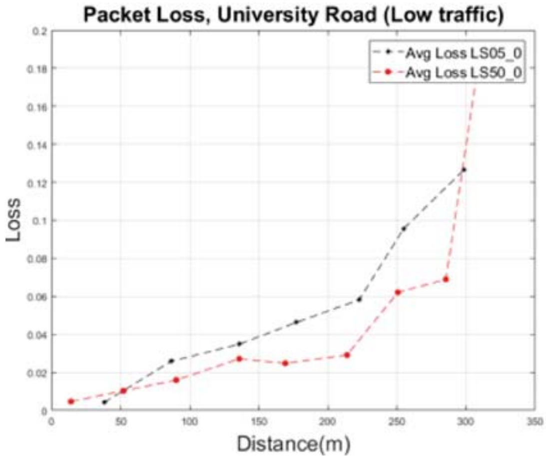


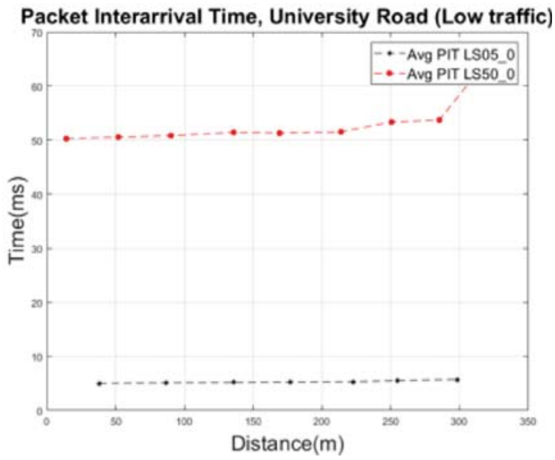
Fig. 4.3: Data-point Concatenation in Moving Scenario

4.2.3 Results

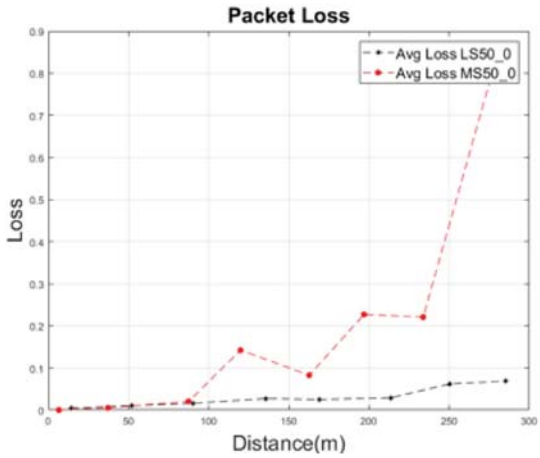
Using the data collected, packet loss vs. distance and PIT vs. distance graphs were generated. For improving the observability, comparing graphs were generated for both



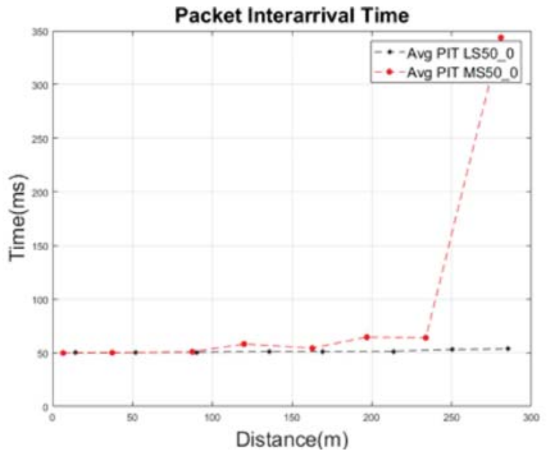
(a) LS05_0, LS50_0 Packet Loss



(b) LS05_0, LS50_0 PIT



(c) MS50_0, LS50_0 Packet Loss



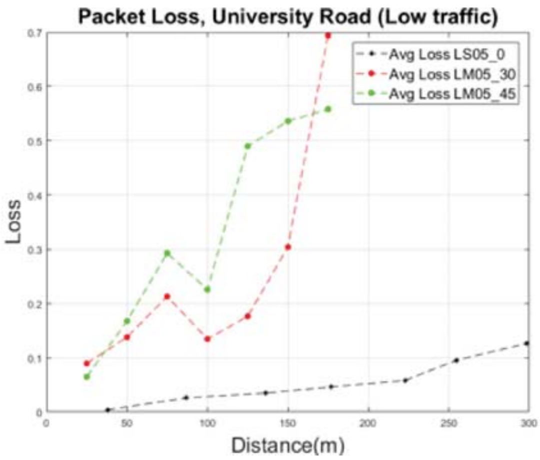
(d) MS50_0, LS50_0 PIT

Fig. 4.4: Preliminary Test Results: Static Scenario

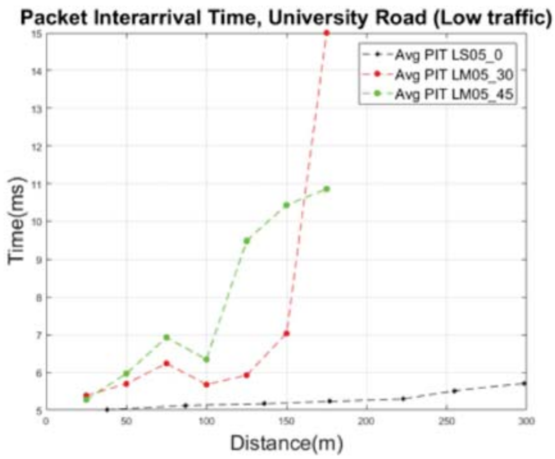
scenarios, which are demonstrated in Fig. 4.4 and Fig. 4.5.

As seen in the results of the static test, the range of the system is around 300m. The packet loss in the moderate traffic scenario shows a higher packet loss ratio and slightly higher PIT values. Also, at a 5ms transmission interval, the system is at its highest performance and it can be observed that there are more losses in this setting than in the 50ms setting. This was due to the receiver not being able to process as fast as it receives messages.

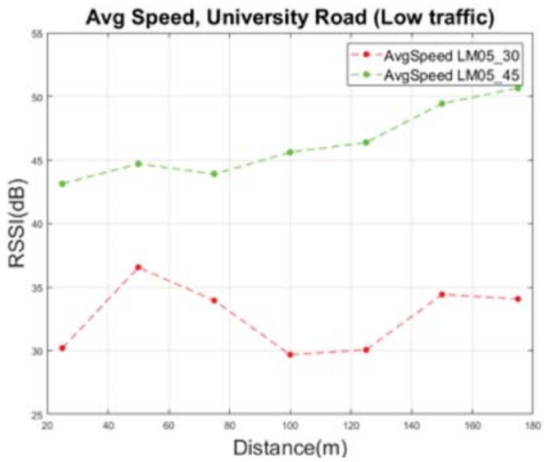
Graphs in Fig. 4.5 compares two speeds and the static scenario. This shows a drastic difference between the static and moving scenarios. This is expected as the receiver is mounted in a moving vehicle and it introduces more interferences. Also, by plotting the confidence intervals as in Fig. 4.5d and Fig. 4.5e, it can be observed that there is a lack of data points in this test.



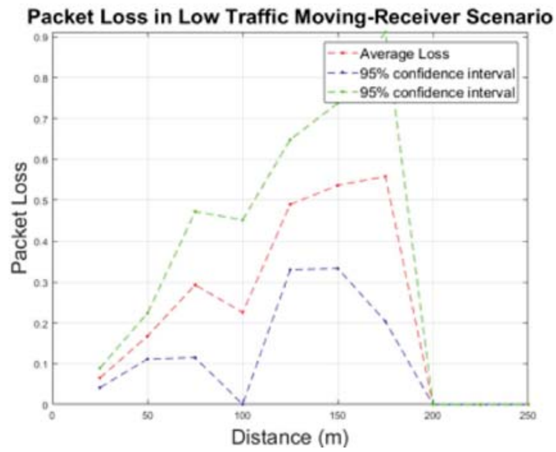
(a) LM05_30, LM05_45 Packet Loss



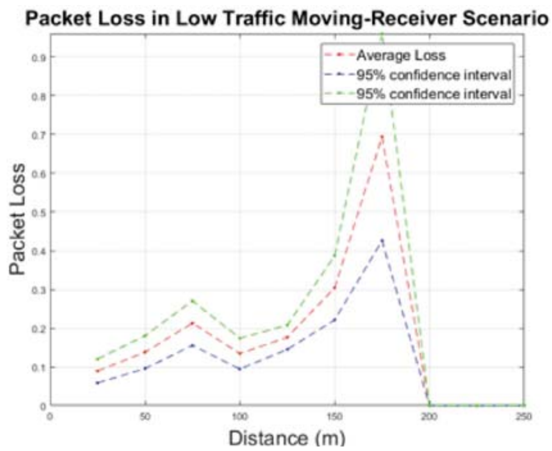
(b) LM05_30, LM05_45 PIT



(c) LM05_30, LM05_45 Speed



(d) Confidence Interval: LM05_45



(e) Confidence Interval: LM05_30

Fig. 4.5: Preliminary Test Results: Moving Scenario

4.3 Final Experiment

4.3.1 Experiment Design

From the inferences taken from the preliminary test, a final data collection experiment was designed.

Devices that were used in this experiment are the same as the devices used in the preliminary test. Except for the GPS recorder devices, which were replaced with Real Time Kinematic (RTK) devices. These are more accurate than regular GPS sensors.

For the location, a road stretch in Gampaha, Sri Lanka was chosen. This was approximately 740m long and straight. This location is shown in Fig. 4.6. This road stretch was devided into two and the RSU device was placed around the center, as seen on Fig. 4.6.

The experiment is same as the moving scenario of the preliminary test. The vehicle starts at an end of the road and drives towards the center. As soon as it passes the RSU, RSU transmissions are stopped.

The packet information and GPS coordinate and speed data was logged in Raspberry pi device with timestamps. These data was used to calculate PIT, PDR and the MR and ER of the system.

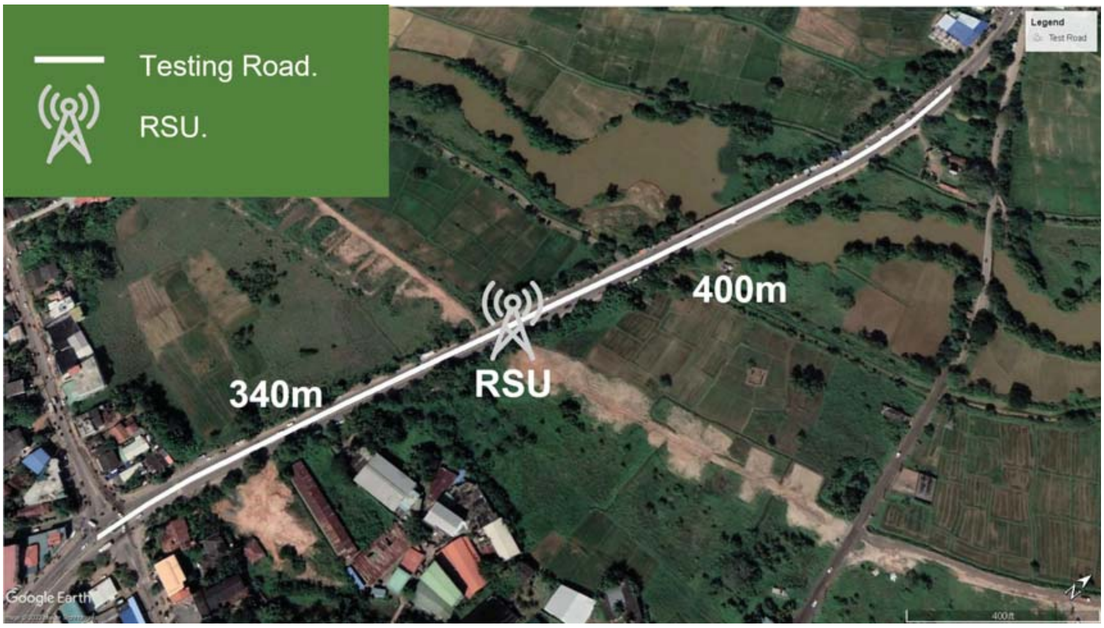


Fig. 4.6: Selected Location (7° 5’ 42.63” N, 79° 59’ 26.80” E)

The experiment variables considered were the vehicle speed(v) and packet transmission interval(T_B). Three speeds and four transmission intervals were chosen. Multiple iterations of the experiment were conducted per one set as the preliminary test had a very low confidence interval due to the lack of data points. This information is presented in the Table. 4.3. These data points were consolidated into distance cluster points of 10m radius as in the preliminary test.

Even though the test was conducted in a 300m long road stretch, the number of data points in the latter ends was low. Hence, the evaluation was conducted in the first 200m range.

TABLE 4.3: Data Collection Campaign: number of data points collected [13].

v \ T_B	**5 ms**	**10 ms**	**30 ms**	**50 ms**
30 km/h	13001	7698	6580	4690
45 km/h	17209	4856	4284	2619
60 km/h	7045	5782	2950	2534

4.3.2 Evaluation

As mentioned in previous chapters,for the evaluation, the following matrices were chosen.

- Average PDR
- PIT
- Probability of Situation Awareness Blackouts
- Range: MR and ER

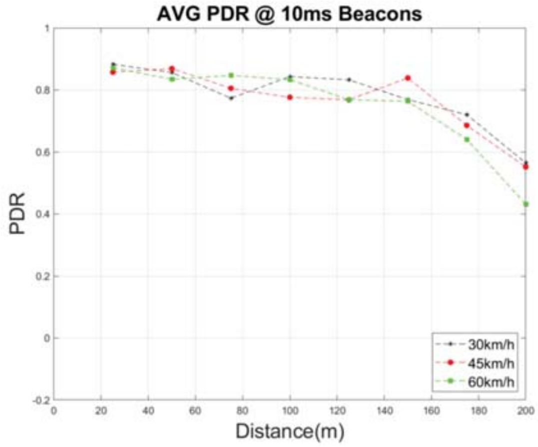
4.3.3 Results

4.3.3.1 Average PDR

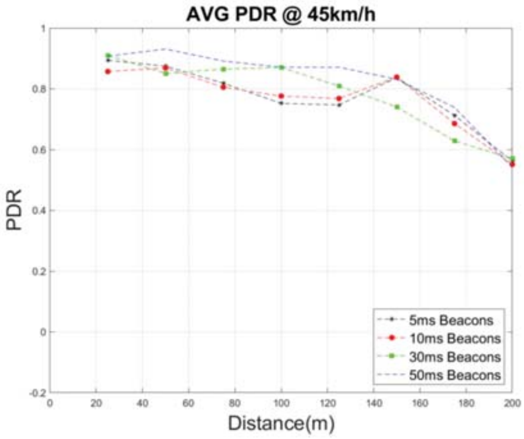
The average PDR is also calculated using the clustering technique introduces in the previous section. Each packet has a sequence number embedded in its body. This is analogous to the number of packets transmitted. The receiver decodes the packet and records these sequence numbers. Later on, these are used to identify the number of packets lost in the transmission in each packet cluster. This value is calculated per iteration and averaged per configuration. These values will be used to identify the ER of the system as followed by Huang et. al. [6]. The 10ms transmit interval and 45 kmh^{-1} scenarios are shown in Fig. 4.7 below.

4.3.3.2 PIT

The receiver records the time a packet is received. This is recorded in microsecond precision and the clock starts when the device is turned on. Therefore, it has no



(a) Average PDR in 10ms Transmission Interval Scenario

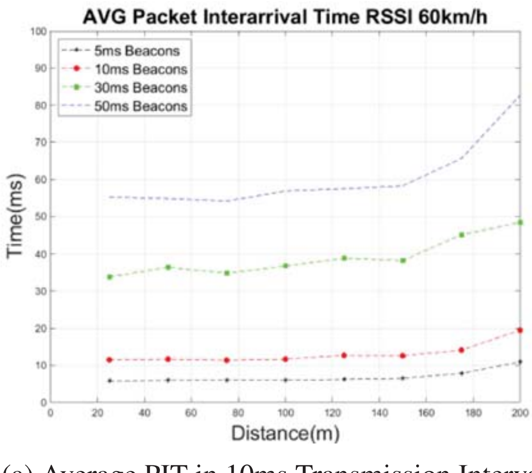


(b) Average PDR in 45 kmh^{-1} Scenario

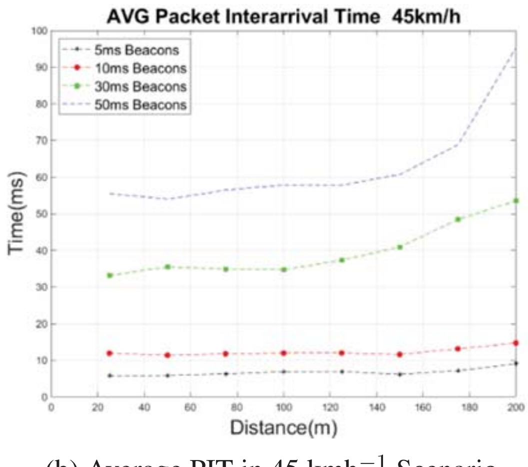
Fig. 4.7: Averaged PDR Results

reference to the actual time. Using the same clustering technique as earlier, the time between two consecutive packet receptions is calculated and averaged to get the PIT at one location. These values are then averaged over the iterations of the test. The 10ms transmit interval and 45 kmh^{-1} scenarios are shown in Fig. 4.8 below.

Further, defining ER as the range where PDR < 50%, implies that the PIT at the edge of the considered ER would be 200ms. However, in the Fig .4.8, the average PIT is well below 200ms in the full 200m test range.



(a) Average PIT in 10ms Transmission Interval Scenario



(b) Average PIT in 45 kmh^{-1} Scenario

Fig. 4.8: Averaged PIT Results

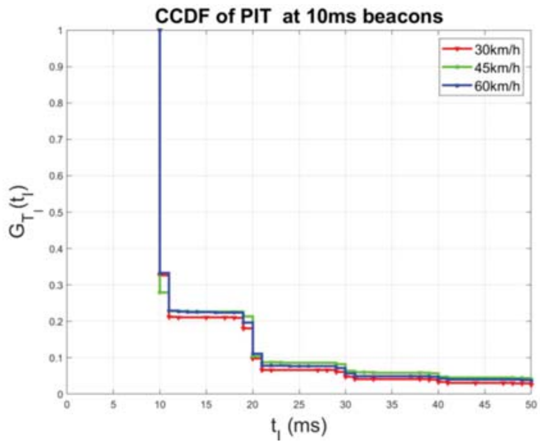
4.3.3.3 Probability of Situation Awareness Blackouts

Situation awareness blackouts are observed by the authors of [36] using complementary cumulative distribution functions (CCDF) of the PIT values. CCDF is calculated using Eq. 4.1 where $G_{T_I}(t_I)$ is the CCDF.

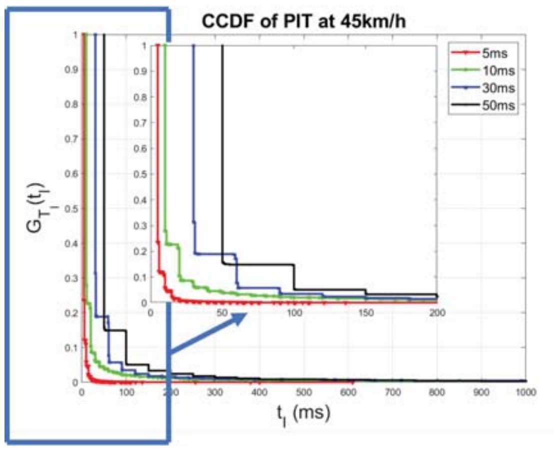
$$G_{T_I}(t_I) = Prob(PIT > t_I) \tag{4.1}$$

The Fig. 4.9 and Fig. 4.10 shows the generated CCDF graphs of 10ms, 50ms, 45kmh^{-1} and 60kmh^{-1} scenarios. If PIT > 1s was chosen as the threshold to identify the blackouts as used by the authors of [36], from Fig. 4.10 it can be observed that the occurrences are extremely rare making the probability of blackouts low.

Further, the Tables 4.4 and 4.5 calculates the probability of a blackout at PIT >

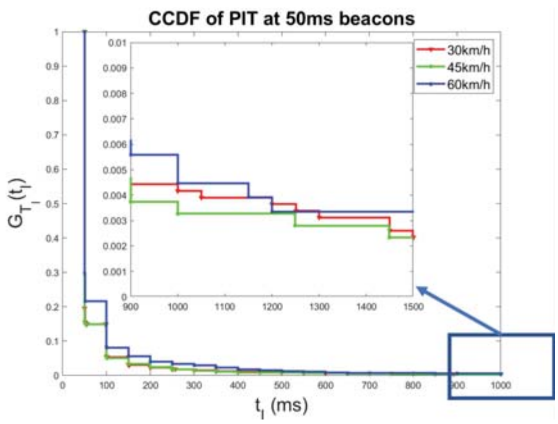


(a) CCDF in 10ms Transmission Interval Scenario

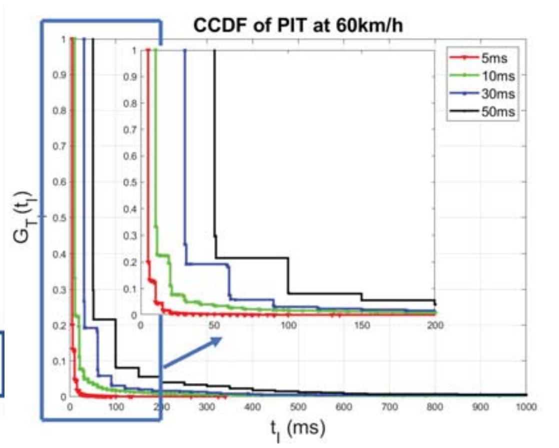


(b) CCDF in 45kmh^{-1} Scenario

Fig. 4.9: CCDF Results



(a) CCDF in 50ms Transmission Interval Scenario



(b) CCDF in 60kmh^{-1} Scenario

Fig. 4.10: CCDF Results in the Worst Test Scenario

TABLE 4.4: Probability of Situation Awareness Blackouts at 45 kmh^{-1} Speed.

T_B \ P	**5 ms**	**10 ms**	**30 ms**	**50 ms**
$P_{BO}(x10^{-4})$	0	2.352	8.475	17
$P[T_I > 200ms](x10^{-4})$	1.99	6.665	60	100

TABLE 4.5: Probability of Situation Awareness Blackouts at 10ms Beacon Interval.

v \ P	**30 kmh^{-1}**	**45 kmh^{-1}**	**50 kmh^{-1}**
$P_{BO}(x10^{-4})$	2.971	2.352	1.959
$P[T_I > 200ms](x10^{-4})$	7.639	6.665	7.834

200ms, which still is considerably low. This 200ms threshold was chosen due to the following reasons. One paper that this experiment was based on was [6], where they define ER as where the PDR keeps under 50%. They were using DSRC which implies, at the edge of the ER, the PIT should be 200ms. Therefore, to compare if and how better the new system is compared to a DSRC based system, this test was conducted.

4.3.3.4 Operable Range MR and ER

For calculating the maximum range, the first received packet is identified in each iteration of the experiment. Then using the GPS coordinate recorded at the timestamp of the recording, the distance is calculated to that location from the RSU. This value is averaged over one experiment configuration to find the MR in that particular configuration. MR values derived from this are displayed in Table 4.6. The MR is always above 300m. However, DSRC can achieve a 900m MR [6] which is using a 33 dBm power and 5 GHz frequency.

In the ER calculation, the definition of [6] was used; range where the PDR > 50%. Using the clustering technique mentioned above, the PIT values are calculated at each distance for each iteration of the experiment. Using these PIT values, the distance where PDR goes below 50% is identified. These values are averaged across each speed and transmission interval configuration to calculate the ER values, which are shown in Table 4.7. ER is almost always in the 200m range.

TABLE 4.6: MR Observed in Each Configuration.

T_B \ v	**5 ms**	**10 ms**	**30 ms**	**50 ms**
30 km/h	329.25	335.83	313.71	311.56
45 km/h	350.97	336.17	329.44	335.85
60 km/h	332.00	330.54	328.04	334.68

4.3.4 Integrated System

The performance of the integrated system was evaluated by combining the experimental data of the Wi-Fi-based system and the data available in the literature, which was presented in [13]. Here, the Information Update Interval of the system will be used instead of PIT, as it provides a clearer definition of the metric. IUI is the time period from when an activity happens in the real world until the driver receives the necessary information regarding that activity. In the case of this system, this can be interpreted as the PIT.

First, the PIT graph was generated for DSRC communication using data found in the literature. This is plotted in Fig 4.11. Then the expected Information Update Interval values for the Integrated Vehicle-to-Vehicle (I-V2V) system are calculated as shown in Fig. 4.12 using the relationships noted in Table 4.8. Maximum IUI values within the ER of an I-V2V system can be extracted from the above calculation. These are shown in Table 4.9. From Fig. 4.11 and Table 4.9, it can be observed that changing the T_B has a significant effect on the IUI. Hence, the capability to set an application-specific T_B in the Wi-Fi section can be considered an advantage of this system. Also, with this capability, the maximum IUI within the ER of the Wi-Fi subsystem of an Integrated Infrastructure-to-Vehicle (I-I2V) system can be set significantly lower than that of the DSRC I2V system, which is an improvement of reliability and efficiency.

4.3.5 Discussion

The previous empirical evaluation tests the suitability of the Wi-Fi component of the integrated system to operate in a high-speed vehicular environment. Then goes on to extrapolate the integrated system performance using data. found in literature. The results suggest that the system is a viable solution for some ITS applications. As the Wi-Fi-based experiment was a significant part of the research, the results are discussed under the following two topics to establish what the Wi-Fi-based experiment results affect the integrated system.

- Wi-Fi component
- Integrated system

TABLE 4.7: ER Observed in Each Configuration.

v \ T_B	**5 ms**	**10 ms**	**30 ms**	**50 ms**
30 km/h	219	209	220	289
45 km/h	216	209	246	248
60 km/h	195	191	247	271

TABLE 4.8: IUI Calculation for H-V2V and H-I2V.

	DSRC	Wi-Fi
H-I2V	$IUI_H = PIT_D + 0$	$IUI_H = 0 + PIT_W$
H-V2V	$IUI_H = PIT_D + PIT_W$	

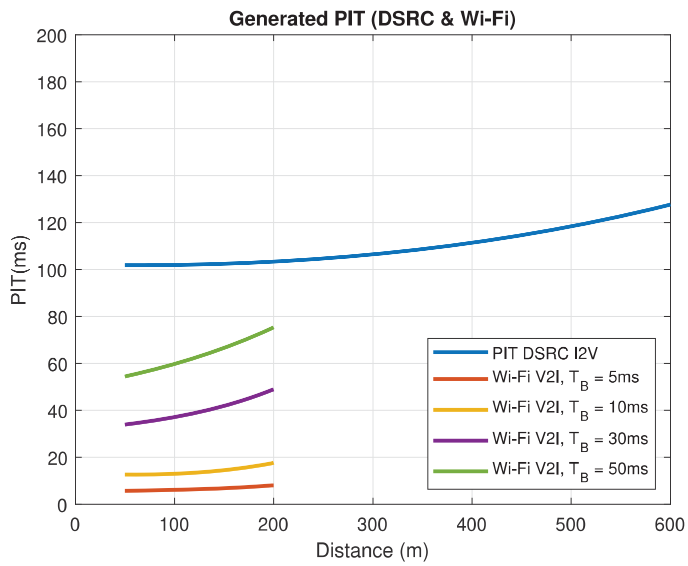


Fig. 4.11: Generated Fit Curved for the Average PIT of DSRC and Wi-Fi Communications. T_B = 10ms,υ = 45kmh^{-1}

Furthermore, ITS minimum performance specification put forth by 5GAA [14] and ETSI [15] will be used in the upcoming sections to discuss the acquired performance data. Both these authorities define a set of distances and IUI for many ITS applications.

Apart from transmission-related delays, another common delay applies in the encryption-related activities for the W-OBU and W-RSU devices. A 1300ms delay will occur when retrieving the AES key from the server. However, this will typically be once a day by definition of the system. Further, these devices will encounter a 150μs and 200μs delays in encryption and decryption. However, these delays compared to the delays in transmission (PIT) are negligible.

4.3.5.1 Wi-Fi component

From the experimental data evaluation, the MR and ER of the system can be determined as 300m and 200m. However, when it comes to implementing applications on devices, there are more factors to be considered. The most important factors to be considered are;

- Range

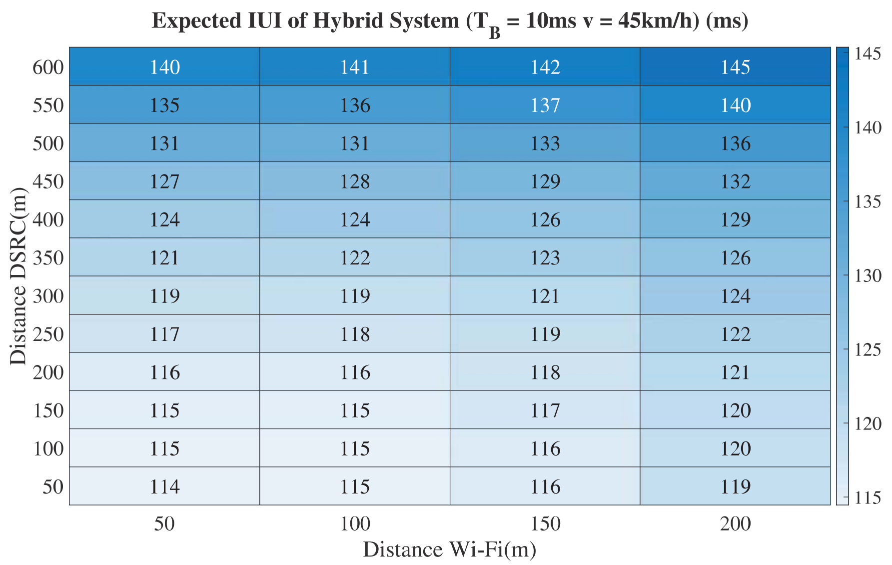


Fig. 4.12: Expected IUI Values of the Hybris System (ms). T_B = 10ms,v = 45kmh^{-1}

TABLE 4.9: Maximum IUI values within the ER of an I-V2V system

T_B / v	**5 ms**	**10 ms**	**30 ms**	**50 ms**
30 km/h	135	146	176	205
45 km/h	136	145	177	203
60 km/h	153	164	190	214

- IUI
- Blackouts

Previously, the probability of a blackout > 200ms occurring was identified to be negligibly small. Hence, the number of factors can be reduced to 2.

IUI and distance specifications provided by 5GAA and ETSI of a few applications extracted from [14], [15] are shown in Tables 4.10 and 4.11. The applications that are feasible to be implemented using the Wi-fi based system are highlighted in blue. Note that these are all I2V applications.

Few promising applications selected from Tables 4.10 and 4.11 are discussed in the Table 4.12. For instance, if the Vulnerable road user detection application were to be implemented using the novel system, it would have a maximum communication range of about 300m. As this is a safety-critical application, 10ms transmission intervals should be used for the transmitter, which will give an approximate 200m range where the PDR is >50%.

As discussed in [73], with appropriate T_B, some other I2V applications can also be implemented using this system such as roadwork ahead, dangerous bend ahead, etc where vehicle speeds are maintained under 70kmh^{-1}.

TABLE 4.10: Range and IUI Requirements - 5GAA [14].

< 100 ms	**= 100 ms**	**> 100 ms**
See-Through for Pass Maneuver (50ms, 100m)	Intersection Movement Assist (100m)	Lane Change Warning (400ms, 28-83m)
Vulnerable Road User Detection (min – 20ms, max -100ms,150m)	Hazardous Location Warning (300m)	Traffic Jam Warning (200ms,1 – 300km)
	Autonomous Vehicle Cross-traffic Turn Assist (350m)	Emergency Brake Warning (120ms,360m)

TABLE 4.11: IUI Requirements - ETSI [15].

< 100 ms	**= 100 ms**	**> 100 ms**
Pre-crash Sensing(50ms)	Vulnerable Road User Detection	Intersection Management (500ms)
Emergency Brake Warning(<100ms)	Emergency Vehicle Warning	Electronic Toll Collection (200ms)
Slow Vehicle Warning(<100ms)	Roadwork Ahead Warning	Traffic Information and Routing (500ms)

4.3.5.2 Integrated system

The integrated system includes 3 communication links; DSRC, Ethernet and Wi-Fi. Processing and propagation delays of DSRC and UDP are in the μs range [74], [75], [76]. Also the authors of [77] shows that the losses in UDP are «0.5%, which is much lower than that of DSRC and Wi-Fi and can be neglected.

Since there are 3 nodes in the integrated system, both I2V (I-I2V) and unidirec-

TABLE 4.12: Applicability and T_B Configurations.

ER (m)	T_B**(ms) and Blackouts**	**MR (m)**
Vulnerable Road User Detection (avg. speed 45 kmh^{-1}).		
200	10. Blackout probability is negligible.	>300
Hazardous Location Warning (avg. speeds 45/60 kmh^{-1}).		
200	10, 30 or 50. Blackouts are not a significant concern for static hazards. Hence, 50 ms may be selected	>300
Electronic Toll Collection (avg. speed 60 kmh^{-1}).		
200	50. Blackouts are not a concern.	>300

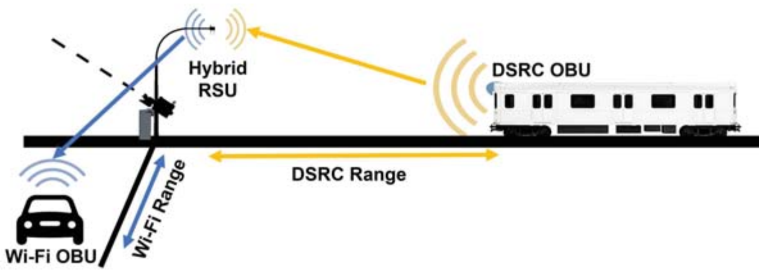
tional V2V (I-V2V) applications can be discussed. For example, a hazardous location warning signs with an I-RSU device is capable of providing necessary messages to both D-OBU and W-OBUs; this is an I-I2V application. For a level crossing application as shown in Fig. 4.13, where the train/tram is equipped with a D-OBU and the crossing has an I-RSU transmitting warnings to both D-OBU and W-OBU equipped vehicles in the vicinity is an example of an I-V2V application.

This example application can be taken as a generic emergency vehicle warning application too. Then there are 2 scenarios for the range. As shown in Fig. 4.14 point *a* and point *b* illustrates scenarios where,

- The emergency vehicle's path aligns with the W-OBU's path. Eg - Fire truck and ambulance warnings.
- The emergency vehicle's path crosses the W-OBU's path. Eg - Level crossing warnings.

Next, two illustrative applications will be discussed to solidify the reader's understanding, which is also presented in [73].

1. I-V2V System: Assume that the vehicle with the W-OBU is travelling at 70kmh^{-1} in the direction of the level crossing, while the train equipped with the DSRC OBU is travelling at 100kmh^{-1}. The I-RSU at the crossing will be informed of the arrival of the train when it is 650m (the ER of DSRC according to [6]) away.



(a) Level Crossing Application

(b) In-Vehicle Signage

Fig. 4.13: Example Application

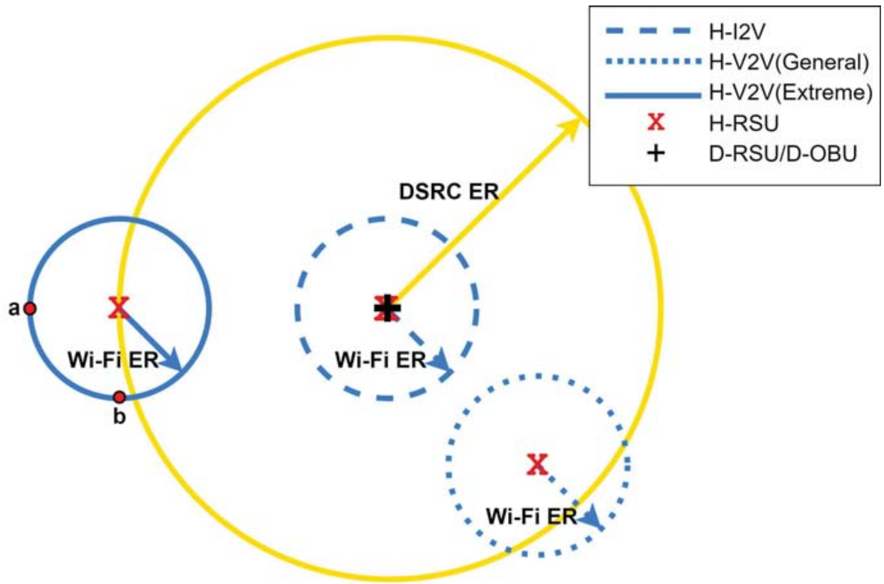


Fig. 4.14: I-V2V Range

This leaves 23s to notify the vehicle travelling towards the crossing. Assuming a maximum deceleration of 4.6ms^{-2} [78] for the vehicle concludes that the vehicle can safely come to a stop in 7s, in which time it will travel 112m. Since the Wi-Fi ER is 200m H-RSU, this novel system meets the requirements for this application.

2. I-I2V System: Consider a pedestrian detection application at a pedestrian crossing where an I-RSU is detecting and transmitting warnings to the on-coming traffic. Assuming the vehicles are travelling at 50kmh^{-1} and the maximum deceleration is 4.6ms^{-2} and a 1s window for the driver reaction time, the stopping distance can be calculated and shown to be 35m. With a 200m range I-RSU, this application is also a feasible application.

4.3.6 Conclusion

This section summarises the experimental findings in the context of the proposed DSRC/Wi-Fi integrated communication system, with emphasis on how the experimentally measured Wi-Fi performance combines with established DSRC characteristics to determine overall system behaviour and feasibility.

Many studies in the literature that investigate integrated communication systems for intelligent transportation applications focus primarily on performance metrics, while the cost of deployment and on-board equipment is often not explicitly addressed. This omission has become a significant barrier to large-scale ITS penetration, particularly in developing regions [4], [9]. The experimental study presented in this thesis was therefore designed to evaluate the feasibility of using Wi-Fi in combination with DSRC as a means of addressing the cost limitations associated with conventional V2X deployments [4], [5], [13], [73], [79].

Based on current (2025) market prices, the addition of a Wi-Fi subsystem to the integrated architecture incurs a cost of less than USD 15, which is significantly lower than the cost of deploying an additional DSRC transceiver. Furthermore, Wi-Fi-enabled COTS devices are widely available from many manufacturers, in contrast to DSRC devices, which are produced by a limited number of vendors. This cost and availability advantage makes Wi-Fi particularly attractive for extending ITS functionality in cost-sensitive deployments.

From a performance perspective, the experimental evaluation demonstrated that the Wi-Fi subsystem provides reliable short-range dissemination of safety messages when integrated with DSRC infrastructure. Using a packet delivery ratio threshold of 50

PIT analysis further showed that, within the Wi-Fi effective range, the temporal performance of the integrated system remains stable, with PIT values typically below 200 ms for short beacon intervals. Larger PIT variations were observed primarily outside the effective range, where higher packet loss occurs. When these results are considered together with DSRC transmission characteristics reported in the literature, it becomes evident that the information update interval of the integrated system is governed mainly by DSRC transmission intervals, while Wi-Fi determines the reliability of the final delivery stage.

Although the communication range of Wi-Fi is lower than that of DSRC, the short information update intervals achievable with Wi-Fi beaconing partially compensate for this limitation. Consequently, implementation of ITS applications using the proposed integrated architecture requires careful selection of both application type and transmission interval. Applications that benefit from frequent updates within a localized region are particularly well suited to the integrated system, whereas applications requiring long-range V2V awareness may remain better served by standalone DSRC solutions.

Overall, the results highlight a clear functional separation within the integrated architecture. DSRC enables long-range detection and early acquisition of safety-critical information, while Wi-Fi provides localized, low-cost dissemination within the final communication zone. As a result, the effective range of the integrated system is bounded by the Wi-Fi segment, whereas the information update interval is constrained primarily by DSRC transmission behaviour. These findings confirm that the proposed integrated system offers a practical balance between performance and cost and can support a subset of ITS applications in a cost-effective manner. The insights gained from this experimental evaluation provide a foundation for the modelling and performance prediction analysis presented in the following chapter.

CHAPTER 5

SYSTEM MODELING

5.1 Introduction

The previous section concluded that the novel system is capable operating in ITS applications in vehicular environment with proper planing. The next and the final step of this study is to provide a method for the selection of the transmission interval for specific ITS applications. This can be achieved by developing a model to predict the behaviour of the novel system. The considered methods of modeling and selection has been discussed in previous chapters. To add to that, in this application, the model needs to develop a relationship between distance and PIT. As seen in Fig. 5.1, this will not be possible with generic methods. This is due to the fact that there are only a handful of high PIT values and that is not enough to change the best-fit curve. This solidifies the previous decision to develop a neural network to predict the performance of the Wi-Fi system.

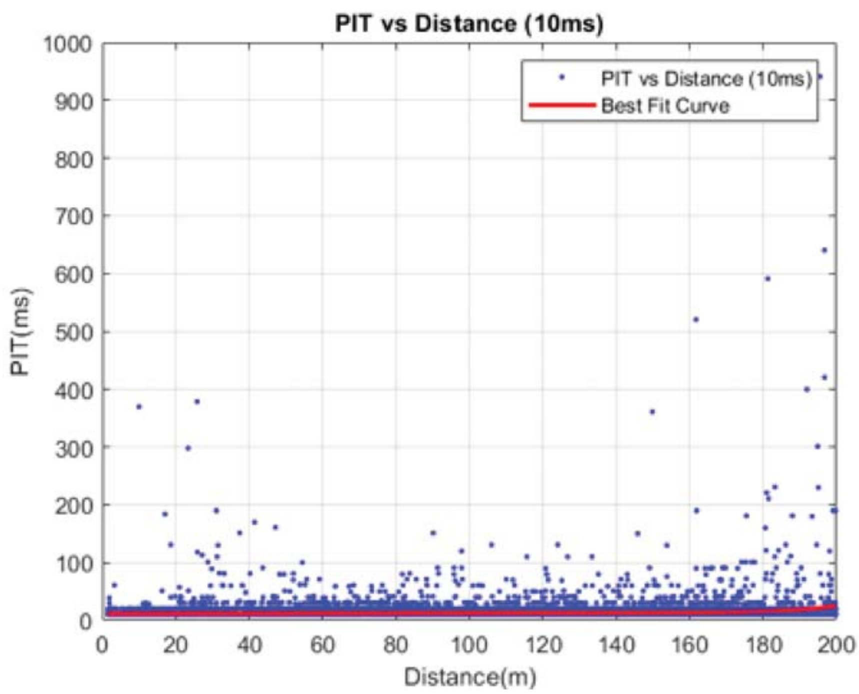


Fig. 5.1: Fitting a Curve to Distance Vs PIT Values

5.2 Proposed model

As mentioned in previous chapters, Bi-directional LSTM (Bi-LSTM) was designed for the model. This model is shown in Fig. 5.2. The model is given the following data,

- Distance
- Speed
- RSSI
- Beacon interval/Transmission interval

This data is fed to a Bi-LSTM and then a multi-layer perceptron (MLP). Finally, it will output the predicted PIT at that distance. Being a Bi-LSTM, it should be given an array of data as the input. This should include data points from the past and future of the data point the model is going to predict. This process is shown in Fig. 5.3.

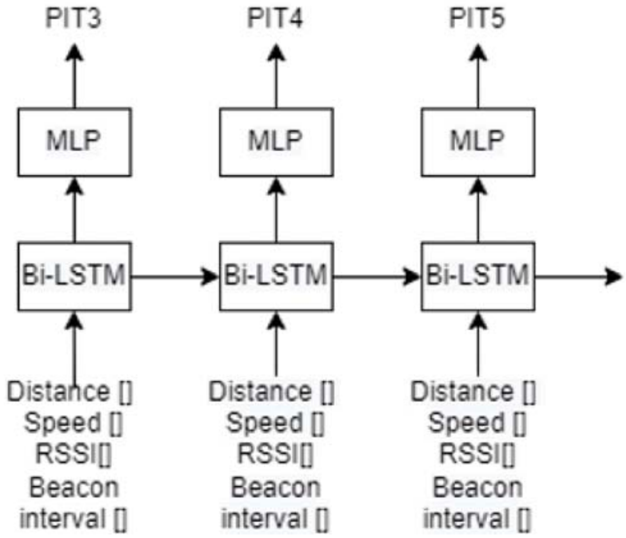


Fig. 5.2: Proposed Model

This model was implemented using Python (Keras, TensorFlow). The data set was divided into 3 parts.

- 70% of data for training.
- 20% of data for validation.
- 10% of data for testing.

The model was trained for 500 epochs total using 70% of the data set, and the final prediction was shown in Fig. 5.4b. A more detailed view is shown in Fig. 5.4a. The model was evaluated using MSE, RMSE, and R^2 values taken at 200 epochs and 500 epochs. These are shown in Table 5.1. The table also concludes how well the model fits the system.

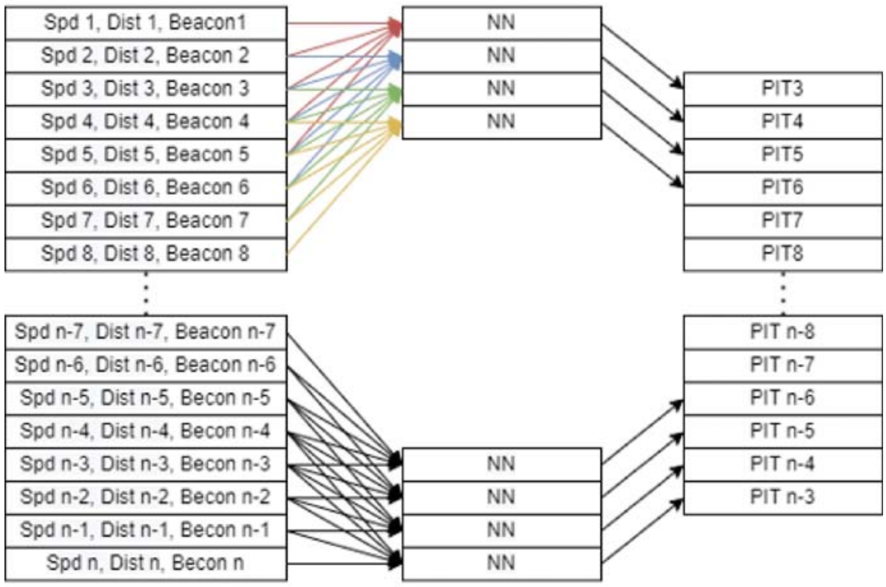
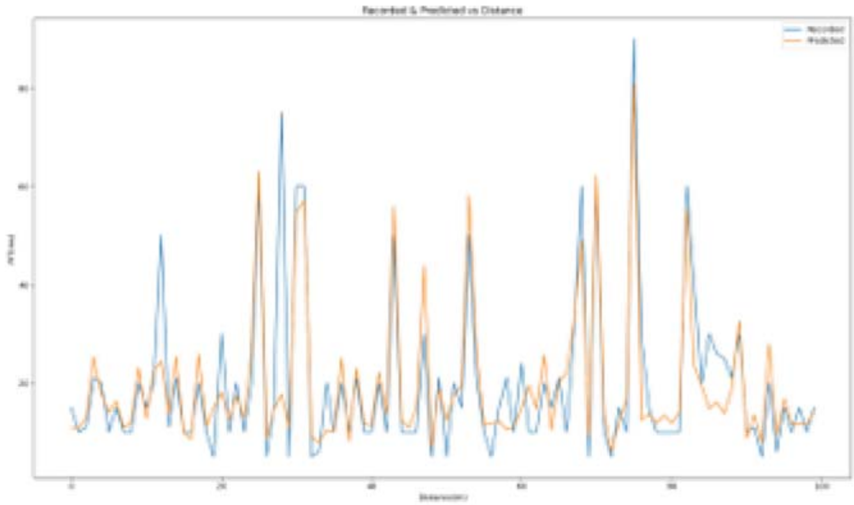


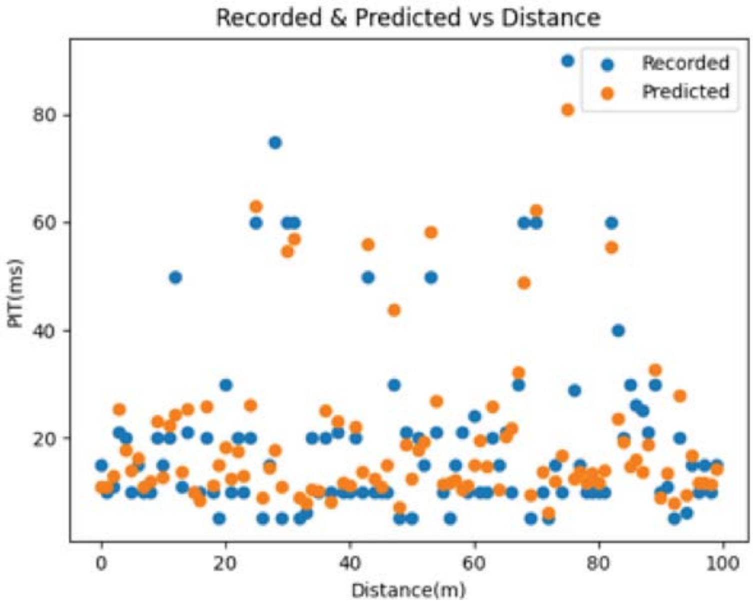
Fig. 5.3: Process of the Neural Network

5.2.1 Application

As mentioned earlier, the intention of the model was to assist with selecting the transmission interval of the Wi-Fi subsystem of an H-RSU. An application was developed to improve the user-friendliness of this. The flowchart of the selection process using the application is shown in Fig. 5.5. The user is expected to enter the required range, the average speed of vehicles traveling in the area, and an arbitrary beacon interval/transmission interval. Then, the application will generate a predicted distance vs PIT graph. The user can analyze this graph and decide to select the entered transmission interval, or retry with another interval value. Two examples such generated graphs are shown in Fig. 5.6.



(a) PIT Vs Distance Prediction (Zoomed-in)



(b) PIT Vs Distance Prediction

Fig. 5.4: Example Application

TABLE 5.1: Maximum IUI values within the ER of an I-V2V system

Metric	**Description**	**200 Epochs**	**500 Epochs**	**Reference Standard**
MSE	Mean Squared Error (average squared prediction error).	12.19	10.82	IEEE Std 754 regression range ($<$ 15)
RMSE	Root Mean Squared Error ($\sqrt{\text{MSE}}$); measures average deviation from ground truth.	3.49	3.29	Acceptable when within 10% of mean values
R^2	Coefficient of Determination; measures correlation strength between predicted and true values.	0.8157	0.9205	Strong fit if $R^2 > 0.9$

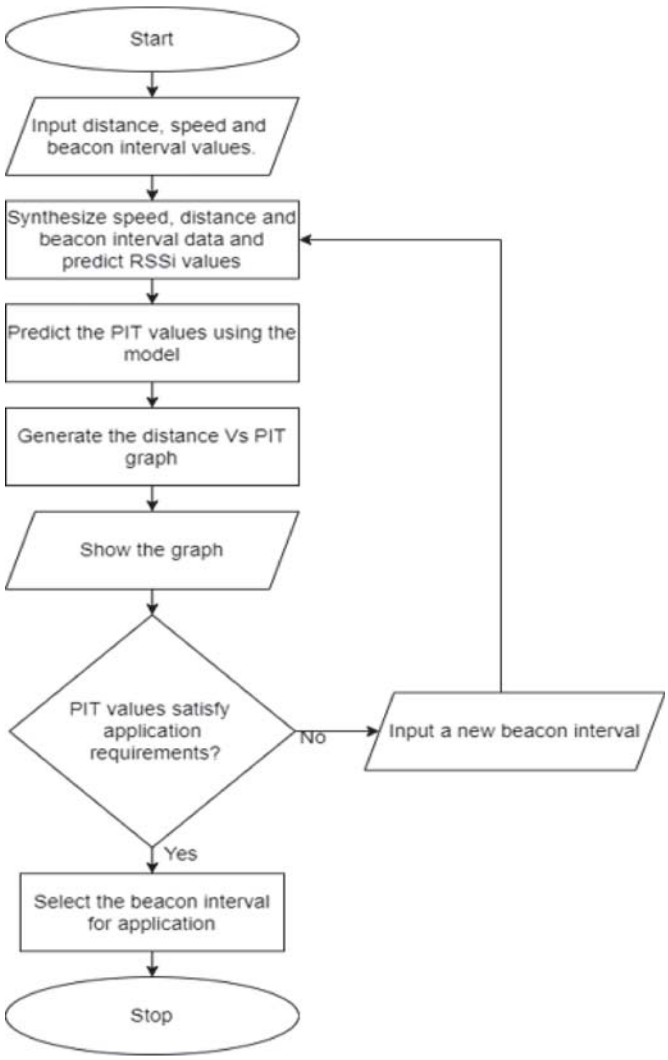


Fig. 5.5: Transmission Interval Selection Process

(a) PIT Vs Distance Prediction (Zoomed-in)

(b) PIT Vs Distance Prediction

Fig. 5.6: Example Application

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusion

This study was planned to design and develop an integrated communication system to reduce the cost of developing ITS applications and improve the take up of such applications. Through the research conducted, the design, development and evaluation of a dual communication system has successfully been carried out in this study. A Wi-Fi-based communication mechanism was developed which can be included into a V2X communication environment with DSRC and C-V2X technologies for a fraction of the cost. The communication range of this novel system has been evaluated to be 200m and feasible ITS applications for this system has been discussed in the previous sections. The final system design of the Wi-Fi component can be deployed on most of the COTS Wi-Fi SoCs which is the reason for the low cost. Due to the lower cost and the simplicity of the initial installation this system can be distributed as a retrofitting unit for older vehicles.

6.2 Recommendations

- Further research can be conducted to improve the security and efficiency of the Wi-Fi communication component, particularly with respect to authentication, encryption, and resilience against spoofing and replay attacks in safety-critical ITS applications.

- Alternative low-latency communication methods can be explored to replace the Ethernet link within the H-RSU, such as SPI, CAN, or shared-memory-based interconnects, to further reduce system latency and hardware complexity.

- Future work may investigate the impact of channel congestion and interference in dense deployment scenarios, including urban intersections with multiple H-RSUs and W-OBUs operating simultaneously.

- The proposed system can be extended to support adaptive beaconing strategies, where transmission intervals are dynamically adjusted based on vehicle speed, traffic density, or application requirements to improve scalability and spectrum efficiency.

- Additional field trials under diverse environmental conditions, including non-line-of-sight scenarios, adverse weather, and higher vehicle speeds, would provide further insight into the robustness of the integrated system.

- Integration of the proposed Wi-Fi-based subsystem with emerging V2X standards, such as IEEE 802.11bd and 5G NR-V2X, can be explored to assess backward compatibility and long-term deployment feasibility.

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