Motorway Vehicular Networks with Renewable Energy Powered Access Points

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Abstract

The goal of this work is to consider the potential of using renewable energy only to power roadside units (RSUs), which not only reduces CO2 footprint but also reduces the infrastructure needed in motorway vehicular communication. The thesis begins with collation and analysis of wind and motorway traffic data for the purpose of determining the energy demand of vehicular networks as well as the energy supply obtainable from wind. This is followed by the study of a standalone RSU powered by wind energy. Small size standalone wind energy systems which have benefits of low cost, easy and large scale deployments are implemented for the low power RSUs. The concept of wind energy based rate adaptation is introduced and implemented in the RSU through which RSU can vary transmission power according to the availability of wind energy. This reduces the outage and improves the overall service quality. Traditionally rate adaptation was employed to cater for wireless channel unavailability. A queuing model for the RSU is developed and verified through simulation to evaluate the performance in terms of delay, packet loss and utilisation. Channel fading is considered and the performance of the RSU is re-evaluated in terms of the same quality of service parameters, viz. delay, packet loss and utilisation to investigate the impact of fading in the network.

Next, the reliability of the RSU is redefined in the context of unavailability of sufficient wind power. The transient nature of wind energy

causes the RSUs to either transmit at full data rate or not transmit at all depending on the availability of sufficient energy. Thus, a failure occurs when the wind power is less than the load. Therefore, a framework has been developed for redefining a number of reliability parameters in the context of wind powered RSUs. A detailed wind data analysis was carried out based upon the hourly wind speed obtained from the UK air information resource (AIR) database for a period of five years, to determine the energy model of the deployed micro-turbine. An energy storage device (a small battery) is connected to the micro-wind turbine for improved service quality.

Table of Contents

List of Figures

List of Tables

List of Abbreviations

AC	Access Channel
ACK	Acknowledgment
AFD	Average Fade Duration
AIFS	Arbitration Inter-Frame Space
AIR	Air Information Resource
AP	Access Point
BC	Basic Channel
ASTM	American Society for Testing and Materials
BS	Base Station
CDF	Cumulative Distribution Function
CSMA/CA	Carrier Sense Multiple Access/ Collision Avoidance
CTS	Clear to Send
CW	Contention Window
dB	Decibels
DCF	Distributed Coordination Function
DCH	Double Cluster Head
DIFS	Distributed Inter-frame Space
DOD	Depth of Discharge
DSRC	Dedicated Short Range Communications
EDCA	Enhanced Distributed Channel Access
EENS	Expected Energy Not Supplied

EDNS	Expected Demand Not Served
EIR	Energy Index of Reliability
EIR	Energy Index of Unavailability
ELCC	Effective Load Carrying Capacity
ESP	Electronic Stability Program
FCC	Federal Communication Commission
FDMA	Frequency Division Multiple Access
FI	Frame Information
FOR	Forced Outage Rate
GAF	Geographic Adaptive Fidelity
GPS	Global Positioning System
HGV	Heavy Goods Vehicle
HVC	Hybrid Vehicular Communication
IAT	Inter-Arrival Time
ICT	Information and Communication Technology
IID	Independent and Identically Distributed
ITS	Intelligent Transportation System
IVC	Inter-Vehicular Communications
IVS	Inter-Vehicular Systems
LCR	Level Crossing Rate
LOEE	Loss of Energy Expectation
LOLE	Loss of Load Expectation
LOLP	Loss of Load Probability
LOS	Line of Sight
MAC	Medium Access Control

MANET	Mobile Ad hoc Network
MGM	Matrix Geometric Method
MIVC	Multi-hop Inter-Vehicle Communication
MPR	Market Penetration Ratio
MTBF	Mean Time before Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
MW	Mega Watts
NAV	Network Allocation Vector
OBU	On-board Unit
OFDM	Orthogonal Frequency Division Multiplexing
OLSR	Optimised Link State Routing
PAMAS	Power-Aware Medium Access Control with Signaling
PBP	Packet Blocking Probability
PCM	Power-Control MAC
PCMA	Power-Controlled Multiple Access
PDF	Probability Density Function
PLR	Packet Loss Ratio
PSM	Power Save Mechanism
QoS	Quality of Service
R-ALOHA	Reservation-ALOHA
RR-ALOHA	Reliable Reservation-ALOHA
RSU	Road Side Unit
RTR	Ready to Receive
RTS	Ready to Send

RVC	Roadside-to-Vehicle Communication
SAPS	Small Autonomous Power Systems
SIFS	Short Inter-Frame Space
SINR	Signal to Interference plus Noise Ratio
SIVC	Single-hop Inter-Vehicle Communication
SRVC	Sparse Roadside-to-Vehicle Communication
SSWECS	Small Standalone Wind Energy Conversion Systems
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UMTS	Universal Mobile Telecommunications System
URVC	Ubiquitous Roadside-to-Vehicle Communication
V2I	Vehicle-to-Infrastructure
V2R	Vehicle-to-Roadside
V2V	Vehicle-to-Vehicle
VANET	Vehicular Ad hoc Network
VCN	Vehicular Communication Network
WAVE	Wireless Access in Vehicular Environments
WLAN	Wireless Local Area Network
WSMP	WAVE Short Message Protocol

List of Symbols

A	Cross-sectional area of wind turbine
C	Energy level of battery
D	Diameter
K	Maximum buffer size
M	Vehicular density/ No of vehicles
N	Average number of packets in an RSU
U	Utilisation of the system
W	Average packet delay
k	Number of packets/ Rician factor
q	Vehicular flow
s	Free flow speed
t	Time duration
v	Instantaneous wind speed
α	Scale parameter of Weibull distribution (for wind speed)
β	Shape parameter of Weibull distribution (for wind speed)
λ	Packet arrival rate
μ	Packet service rate
μ	Mean of Normal distribution
ρ	Offered load
ρ	Air density
σ	Standard deviation of Normal distributed traffic load

C_p	Coefficient of performance
E_0	Energy demand of the system in a year
E_t	Transmission energy
E_{t-max}	Maximum transmission energy
E_{t-var}	Variable transmission energy
E_w	Wind Energy
P_B	Packet blocking probability
P_{MAX}	Maximum operational power
P_{Idle}	Minimum operational power
P_{NRA}^{RSU}	Non-rate adaptive RSU power consumption
P_{RA}^{RSU}	Rate adaptive RSU power consumption
P_s	Average packet size
P_t	Transmit power
P_{th}	Receiver threshold power
P_{t-max}	Maximum transmission power
P_{t-var}	Variable transmission power
P_w	Wind power
X_t	Throughput at hour t
$\bar{v}$	Mean wind speed
v_{cut-in}	Cut in speed for wind turbine
$v_{cut-off}$	Cut off speed for wind turbine
$\bar{x}$	Mean service duration
d_{r-max}	Maximum data rate
d_{r-var}	Variable data rate

d_r Data rate

d_v Vehicle data generation rate

e_b Energy per bit

n_i Number of packets in the RSU just after the i^{th} embedded point

q_k Probability of state (k)

α' Scale parameter of Weibull distribution (for wind power)

β' Shape parameter of Weibull distribution (for wind power)

α_j Probability of j packet arrivals in service duration t

β_k Ratio of the probability of the system having k packets to the probability of the system being empty

ρ_c Carried load

1 Introduction

Transportation systems constitute a crucial sector that plays a very vital role in society. The proliferation of vehicles on the road networks has led to increased traffic congestion, accidents and delays despite the progress that automotive industry has made in producing safer and more efficient vehicles in recent years. The incidents of road vehicle crashes are still rife with more than 26 000 people reported to have died on the roads of the European Union (EU) countries in 2013 [1]. The EU statistics reveal that the 1, 387, 957 injuries and 1, 054, 745 road vehicle crashes in 2013 were the lowest numbers of the preceding ten years [1]. Addressing these issues require improved technological capabilities in automobiles and further developments in vehicular communication systems.

The growing trends of 'connected vehicles' in the market, the rapid increase of motorway and urban road networks, and the need to deploy ubiquitous communications networks among large number of vehicles (i.e. 36.5 million vehicles in the UK in 2015 [2]) suggest an imminent growth of vehicular networks potentially comparable to that of the current cellular networks [3]. It is therefore evident that some of the existing operational challenges of cellular topology will be inherited in vehicular networks in addition to the challenge of maintaining seamless connectivity in highly mobile vehicles. Deployment of incumbent mobile technology to support vehicular communication is impractical considering the acute spectrum shortage which restrains higher data rate transmission and the associated large power consumption of complex base stations (BSs). Given that the emergence of vehicular communication networks is at a time that the existing communication technologies are already consuming significant amounts of energy in addition to growing environmental issues, the objective of future vehicular networks should mitigate the problem of low data rates with the use of energy efficient roadside units (RSUs) that connect to the BSs or cloud infrastructure.

The concept of wireless communication deployment in vehicles has necessitated the development of myriads of technologies and applications for vehicular communication networks by the Intelligent Transportation Systems (ITS) councils and various IEEE organisations [4]. Vehicular network is a mobile network which involves communications among vehicles and between vehicles and RSUs. It is a state-of-the-art technology which integrates wireless LAN (WLAN), cellular technology and ad hoc networks to achieve intelligent vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. The participating vehicles, 'smart' vehicles, are equipped with on-board units (OBU) which possess significant computing, communication and sensing capabilities to provide safety and entertainment services to travellers [5], and Global Positioning System (GPS) devices for position or location tracking. Vehicular communication systems are classified into (i) infrastructure-less communication systems, (ii) infrastructure-based communication systems, and (iii) hybrid communication systems which is a combination of (i) and (ii) [6].

The infrastructure-less networks which are called Vehicular Ad hoc Networks (VANETs) have no fixed infrastructures. They are concerned with V2V communication which rely on the vehicles themselves to provide network functionality. They however exhibit characteristics that are dramatically different from many generic Mobile Ad hoc Networks (MANETs) due to mobility constraints, driver’s behaviour, and high mobility [6]. These are distributed, self-organising communication networks built up by moving vehicles, and are thus characterised by a very high node mobility, fast topology changes and constrained mobility patterns based on the road networks. Since these peculiar attributes render the conventional standards and protocols used in MANETs inefficient or unusable in infrastructure-less vehicular communication systems, the design and deployment of robust and resilient routing protocols that meet the quality of service (QoS) criteria are therefore required in these networks for effective data delivery in a multi-hop fashion.

The infrastructure-based vehicular networks benefit from the presence of central infrastructures in the form of access points (APs), RSUs or BSs to offer improved quality, resilience and reliability to the network. The communication here involves vehicle to RSU (V2R) or V2I communication, where the infrastructure provides the vehicles with access to online resources. The fact that a pure V2V network as a standalone network cannot provide access to external online resources such as the Internet makes infrastructure-based vehicular networks desirable, at least in some areas, to provide reliable broadband communication services, access to online resources and local services such as traffic information, tourist information, etc., that are not residing on vehicles. Effective utilisation of channel resources among the vehicles in this centralised communication system is enhanced by an efficient medium access control (MAC) protocol with signaling and coordination by the RSU or BS. The design and development of suitable and resilient MAC protocols therefore constitutes a major research obligation in developing a viable vehicular communication network.

Industries, academia and governmental bodies in America, Europe and Japan have initiated a number of projects and programmes to develop standards and technologies for vehicular network applications in intelligent transportation systems. The Federal Communications Commission (FCC) allocated a frequency spectrum for V2V and V2R wireless communication in 1999. The Commission in 2003 established a Dedicated Short Range Communications (DSRC) Service, which is a short to medium range communication service with the frequency band of 5.850 – 5.925 GHz, developed to support V2V and V2R communications. DSRC is aimed at providing high data rate transfers and low communication latency in small communication zones [7]. The applications of vehicular communications are categorised into safety and non-safety applications. The main safety applications include collision avoidance and cooperative driving, while non-safety applications include entertainment, toll collection, Internet access, gaming by passengers only, multimedia streaming, parking and traffic information [7] [8].

The characterisation and modelling of wireless channel in vehicular environment is essential to provisioning of real time multimedia services that satisfy required QoS. This is necessary considering the erratic nature of outdoor wireless channels whose characteristics vary with time, space and frequency. The combined effect of the unpredictable channel conditions coupled with the high mobility and short connectivity time of vehicles makes the design and development of efficient routing and MAC protocols for vehicular networks a rigorous task. The real performance evaluation of the deployed communication protocols is feasible only if a realistic model of the wireless channel is considered and implemented appropriately.

It is essential that network designs are subjected to thorough testing before deployment to ensure satisfactory performance. This is more so for QoS stringent applications as in vehicular communication systems. The high user mobility and expansive coverage area associated with vehicular networks make practical implementation of a real testbed very laborious and expensive. A reasonable option is to develop simulators which can be used with the practically measured vehicular traces to accurately model the vehicular environment. Accurate performance evaluation of the deployed communication protocols can be done by combining real channel characteristics model with a mobility model. Analytic models built from mathematical tools are also handy for the validation of the simulator’s performances. Necessary modification and tuning of network performance metrics to meet the desired quality criteria can be realised through simulations.

Research efforts have recently been focused on energy-efficiency in vehicular communication networks considering that the energy footprint of Information and Communication Technology (ICT) equipment has become a concern both for economic as well as environmental reasons [9]. Different authors have proposed various techniques to address energy efficiency issues in vehicular networks. Vehicular networks involve communications between vehicles and other battery-fed devices such as pedestrian smart-phones, road transceivers, and sensors that have to be autonomous. Thus, the network power consumption becomes a major concern, and the use of energy-efficient communications is highly desirable. With the BSs having the highest energy consumption among the various units of cellular networks, a substantial amount of energy is consumed in a motorway scenario where BSs are located every 5 km which is the typical coverage limit of base station [10].

The UK motorway scenario considered in this thesis work is the M4 whose traffic traces such as speed, flow, density, inter-arrival time and inter vehicle spacing are available for detailed analysis. The emerging powering option for BSs along motorway length that has both economic and environmental benefits is off grid renewable energy sources. This is due to the high cost of extending the national grid lines that would be grossly underutilised to the isolated motorway locations. Moreover the current prevalent option of deploying diesel generators to these locations has a multiplying effect on the operational cost while compounding the carbon emission dilemma [11]. The “Green Power for Mobile” initiative promises to cut down carbon emissions down by about 6.8 million tons and save up to 2.5 billion litres of fuel with target of 118,000 renewable energy powered BSs deployment in developing countries [11].

Deployment of RSUs with renewable energy sources can significantly reduce the carbon footprint while standalone off-grid wind powered RSUs can as well alleviate common issues associated with grid connected renewable energy farms, and provide ease of operation (deployment and maintenance) in remote areas such as countryside and motorways. Such deployments also eliminate several power systems related issues such as distribution, metering and grid maintenance. With the renewable power generation technologies becoming increasingly cost-competitive and the option of off-grid electrification in most areas and locations with good resources becomes most economic [12], the renewable energy sources in conjunction with fast rechargeable batteries have become an attractive option to power the BSs/RSUs in sparse vehicular environments.

Since achievable renewable energy varies greatly based on the geographic locations and weather conditions, the design of reliable communication systems powered by renewable energy introduces additional complexity, especially in the case of standalone off-grid systems. Wind powered off-grid BSs/RSUs prove a better option in windy countries like the UK, where the solar power is limited in several geographic locations for a substantial period of the year and large photovoltaic modules and energy storage devices are required to produce sufficient energy to meet the expected load demand. The previous studies by authors in [13] investigated the feasibility of a standalone wind-powered RSU in the UK and have shown that the communication Quality of Service (QoS) requirements can be met with a very small battery if a sleep mechanism is employed. However, their study did not encompass reliability aspects. Hence, it is necessary to undertake the reliability analysis and modelling of such an RSU in the context of unavailability of sufficient wind energy. Subsequently, a number of analytic models need to be developed.

In order to minimise power consumption in vehicular communication systems, the number of high power BSs is reduced by deploying pico-cells served by low power RSUs within a macro cell that is served by the BS intermittently. This heterogeneous network offers high data rates with reduced number of BSs while satisfying the QoS criteria [14]. Small size standalone renewable energy systems which have benefits of low cost, easy and large scale deployments are implemented for the low power RSUs. The reliability of these renewable energy systems are investigated to ensure their suitability for vehicular networks by comparing the various traffic loads with the renewable energy profile. The performance of rate adaptive scheme designed for vehicular networks is investigated while implementing the real channel characteristics in the motorway environment.

1.1 Research Objectives

The research objectives of this thesis were:

- To study the vehicular traffic characteristics in a motorway scenario with the view of using models for the traffic flow, density, speed and inter-arrival time based on the recorded data for energy demand model and network simulation.

- To develop viable and reliable renewable energy sources for vehicular networks in a standalone off-grid fashion in a motorway environment.
- To investigate the reliability of the renewable energy powered vehicular networks.
- To develop energy efficient strategies that enhance low carbon footprint for vehicular communication systems.
- To develop and evaluate the performance of renewable energy based rate adaptive scheme with real channel characteristics in motorway vehicular communication systems.

1.2 Research Contributions

In this thesis, the author has

1. Carried out a statistical analysis of measured vehicular traffic data of M4 motorway in the UK to obtain traffic flow, density, speed and inter-arrival time models.
2. Carried out a detailed analysis of wind data for Reading (UK) and some other stations, deployed a micro wind turbine for powering RSU as standalone off-grid entity, compared the instantaneous available wind energy with the vehicular traffic load, and developed a wind energy based rate adaptive scheme that results in better

service quality for the RSU. The power margin of the proposed scheme was compared against that of non-rate adaptive RSU.

3. Investigated the impact of fading on the performance of the proposed wind energy based rate adaptive RSU. The M/G/1/K queue model of the rate adaptive RSU was validated with a Java based event driven simulator.
4. Carried out a detailed reliability study and performance evaluation of standalone wind powered RSUs in a motorway vehicular network using measured wind data for a period of five years and real vehicular traffic profiles of M4 motorway in the UK.

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2. Audu, G.A.; Bhattacharya, S.; Elmirghani, J.M.H, " TDMA-Based MAC (CVTMAC) in Green Vehicular Networks," Next Generation Mobile Applications, Services and Technologies (NGMAST), 2016 Tenth International Conference on, 24-25 Aug. 2016
3. Audu, G.A.; Bhattacharya, S.; Elmirghani, J.M.H, "Reliability and Quality of Service Modelling of Off-Grid Wind Powered Roadside Units in a Motorway Vehicular Environment," Accepted by Elsevier Vehicular Communications (Jan. 2017)

4. Audu, G.A.; Bhattacharya, S.; Elmirghani, J.M.H, "Review of Advances in Energy Efficient Vehicular Communication Systems," to be submitted to Elsevier Vehicular Communications.

1.3 Thesis Overview

Following the Introduction, the thesis is organised as follows:

Chapter 2 presents an overview of vehicular communication networks including their types, applications, environments and technologies. Related works bordering on MAC protocols, energy efficiency, renewable energy and reliability which constitute the basis of the research direction of the thesis are explored. An overview of a mathematical modelling tool (queueing theory) is also presented.

Chapter 3 provides statistical analyses of motorway vehicular traffic and wind data to determine the energy demand of vehicular networks as well as the energy supply obtainable from wind (as this research work is primarily concerned with motorway vehicular networks with renewable energy). Real vehicular traffic traces recorded by inductive loops on the motorway (M4 in the UK) are used to determine the essential traffic parameters such as flow, speed, density and inter-arrival time, which have been largely utilised in the vehicular network simulator and model designs.

Chapter 4 presents a rate adaptive scheme for wind powered standalone (off-grid) RSUs in a motorway environment where the RSUs transmit data at various rates according to the available wind energy to ensure efficient utilisation of available renewable energy. The power margin of the proposed scheme is compared against that of non-rate adaptive RSU.

Chapter 5 presents the performance investigation of RSU while incorporating the motorway channel fading effect. The various performance metrics evaluated both by queue model and simulation include average packet delay, packet loss ratio and utilisation.

Chapter 6 investigates the reliability of wind powered off-grid RSUs deployed in the motorway vehicular networks using reliability and probabilistic indices to define the performance of a single RSU. Wind energy and traffic load models are used to obtain models for various reliability indices with and without a battery.

Chapter 7 brings the thesis to a conclusion with highlights of the key findings and future research directions.

2 Overview of Vehicular Communication Systems

2.1 Introduction

This chapter presents the general outlook of vehicular communication systems. The basic components, infrastructures, environments and the underlying standards of vehicular networks are discussed while the related works bordering on MAC protocols, energy efficiency, renewable energy and reliability which constitute the basis of the research direction of the thesis are briefly explored. An overview of the mathematical modelling tool (queueing theory) and the simulator utilised in the work is presented.

2.2 Applications of Vehicular Communication System

In the literature significant efforts have been reported by several authors to categorise the applications of vehicular communication systems and the type of networks and the protocols that support them [7], [15]. In [7] the applications of vehicular networks are classified into two broad categories: intelligent transportation applications and comfort applications. Georgios et al. [15] introduce a more detailed classification that splits intelligent transport applications into 1) Active road safety applications and 2) Traffic efficiency and management applications. The various applications of vehicular communications are categorised by [15].

2.2.1 Active Road Safety Applications

Researches have showed that a great percentage of road accidents that occur everywhere in the world are largely associated with intersection, head, rear-end and lateral vehicle collisions. Active road safety applications are those applications that are basically meant to minimise the rate of traffic accidents and to enhance the safety of road users. Information such as vehicle position, intersection position, speed and distance heading are shared among vehicles and RSUs to help drivers predict collisions and to avoid them. Hazardous locations on roads such as potholes and slippery sections can also be exchanged between vehicles and RSUs to ensure safe navigation. The major active road safety applications according to [15] - [16] are discussed as follows.

Intersection collision warning: According to [17] intersection collisions constitute approximately 26% of all crashes in the United States while one fourth of fatal crashes occur at or near intersections. Intersection collision being different from lateral collisions that occur in a single direction of traffic flow, involves vehicles in different crossing path directions. To avoid this, warning signals are sent to vehicles that are approaching intersections on the road by other vehicles and RSUs that have the relevant information to forestall or reduce the risk of lateral collisions.

Cooperative Forward Collision Warning: Rear-end collisions are mostly caused by tailgating, distracted driving, speeding or sudden braking ahead of a following vehicle. Rear-end collisions constitute a significant percentage of all accidents. The Cooperative Forward Collision Warning is a system that aims to provide warning to drivers if a collision with a vehicle ahead may occur. Most of the time, drivers' response to emergency situations in front of them is so slow that an initial accident between two vehicles will lead to a chain of colliding vehicles. Through intelligent transport systems application emergency information is propagated among vehicles much quicker than a traditional chain of drivers reacting to brake lights of a vehicle immediately ahead. Imminent rear-end collisions are averted through prediction as each vehicle monitors the actions of its driver and its position and that of nearby vehicles. The vehicle alerts its driver when a critical proximity is detected, hence providing the driver with enough time to intervene and avoid a crash. This technique prevents chains of collisions in vehicle platooning or cooperative adaptive cruise.

Pre-crash Sensing/Warning: Pre-crash sensing is a system that optimises drivers' safety when an impact is imminent. This application requires that vehicles periodically share relevant information with neighbouring vehicles that would make imminent collision predictable. When the occurrence of crash becomes inevitable, the involved vehicles engage in fast and reliable communication to exchange information such as more detailed position data and vehicle size, while the pre-crash information is relayed by the vehicles and the RSU to actuate the vehicle protective devices such as airbags, motorized seat belt pre-tensioners and extendable bumpers to minimise the degree of damages.

Hazardous location notification: Information about hazardous locations such as obstacles on the road, ongoing construction work, potholes or slippery road condition detected by a vehicle or RSU is broadcasted to other vehicles and RSU(s) in the neighbourhood. This application is concerned with generating information about the driving condition at a specific location. When a vehicle experiences an actuation of its Electronic Stability Program (ESP) system due to the hazardous road incident, it retains the information about the location and shares its knowledge with other vehicles in the vicinity. The disseminated safety message received by other vehicles is either signalled to the drivers to enable them to avoid the incident or used directly by the vehicles to automatically optimise their safety systems.

Emergency electronic brake lights: This is a system that enables a vehicle to broadcast a self-generated emergency brake event to the vehicles behind when it brakes hard due to emergency. The host vehicles upon receiving such event information determine the relevance of the event and provide warning to the driver appropriately.

2.2.2 Traffic Efficiency and Management Applications

These applications are concerned with constant updating of local information, maps, and messages of relevance bounded in time and/or space so as to enhance improvement in traffic flow, coordination and assistance. Two practical areas of these applications are speed management and co-operative navigation [18]. In speed management, the regulatory speed limit notification and optimal speed advisory help the drivers to effectively manage their speeds. The regulated speed improves traffic efficiency, enhances smooth driving, improves fuel consumption and guarantees passengers' safety. By co-operative navigation, it is possible for vehicles to travel together closely and yet safely in vehicle platooning. This leads to a reduction in the amount of space used by a number of vehicles on a highway. Thus more vehicles can use the highway without traffic congestion. Invariably, traffic efficiency is improved by managing the navigation through cooperation among vehicles and between vehicles and RSUs. Co-operative adaptive cruise control is another example of this application.

2.2.3 Infotainment Applications

These applications provide comfort and entertainments to drivers and passengers through content sharing between vehicles and provisioned access to Internet services that allow them to browse the webs, shop online and even participate in video conferencing. Passengers can download music or play back-seat passenger games through Internet connectivity with the nodes while on the move.

2.3 Vehicular Network Architectures and Environments

Rapid development in hardware, software, and communication technologies have resulted in increased interest in ITS which involves intelligent or "*smart*" vehicles. Vehicular network is a mobile network designed mainly for communications among vehicles and between vehicles and roadside infrastructures. It integrates wireless LAN (WLAN), cellular technology and ad hoc network to achieve intelligent vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communications. The participating vehicles are equipped with on-board units (OBU) which possess significant computing, communication and sensing capabilities to provide safety and entertainment services to travellers [6], and Global Positioning System (GPS) devices for position/location tracking. Vehicular communication systems are classified into (i) infrastructure-less vehicular communication system, (ii) infrastructure-based vehicular communication system, and (iii) hybrid vehicular communication system which is the combination of (i) and (ii) [7].

2.3.1 Infrastructure-Less Vehicular Communication System

In infrastructure-less vehicular communication systems, the vehicles communicate with each other directly using ad hoc networks called Vehicular Ad hoc Networks (VANETs) or Inter-Vehicle Communication (IVC) [7]. The V2V communication relies on the vehicles themselves to provide network functionality. This architecture employs distributed, self-organising communication networks built up by moving vehicles, and are thus characterised by a high node mobility, fast topology changes and constrained mobility patterns based on the road networks. The V2V or IVC infrastructure-less vehicular system have the benefits of low cost (being a charge free service), easy deployment (no infrastructure overhead) and low delay. In this architecture, the communication is either by a single-hop or multi-hop depending on the distance between the communicating vehicular nodes. These constitute the two types of IVC systems, namely, single-hop and multi-hop IVCs (SIVCs and MIVCs) [5]. In a single hop communication the source and destination nodes are within the communication range of each other and they communicate directly while in multi-hop communication, the source and destination nodes are out of range and require an intermediary node(s) to provide the communication link between the source and destination [19]. Figure 2.1 and Figure 2.2 illustrate the single-hop and multi-hop infrastructure-less vehicular communications. Figure 2.1 captures a single-hop IVC scenario in which vehicles 1, 2, 3 and 8 communicate directly with one another without any intermediary as they all lie within the communication range of one another. Figure 2.2 shows a multi-hop IVC where vehicle 2 and vehicle 5 are outside the communication range of each other but both lie within the communication range of vehicle 8. Communication between vehicle 2 and vehicle 5 is relayed through vehicle 8 as an intermediary node in a multi-hop fashion. Sometimes, more than one relaying node is required in a multi-hop communication depending on the distance between the source and destination nodes. This is however at the expense of service time (delay).

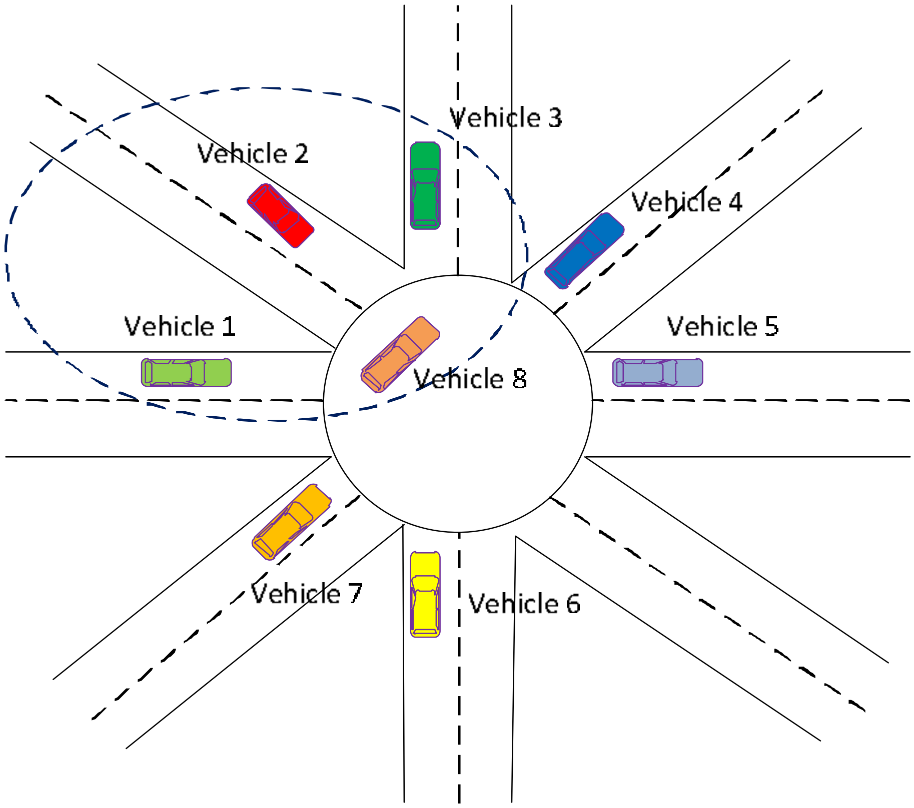

Figure 2.1 : Single-hop inter-vehicle communication system.

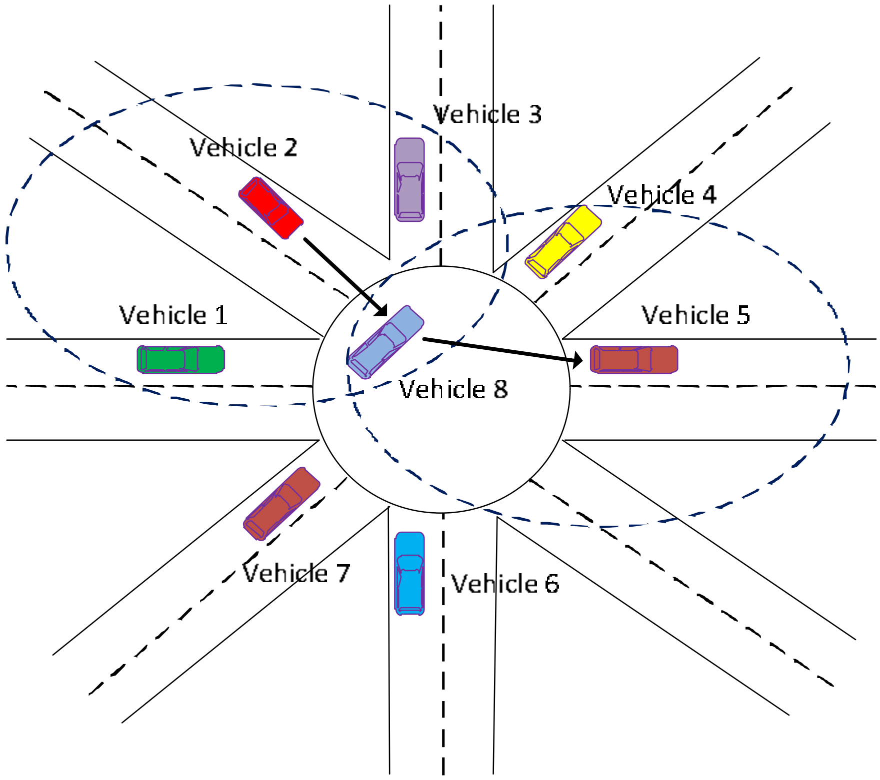

Figure 2.2: Multi-hop inter-vehicle communication system.

The IVC has major drawbacks of low market penetration (MPR) of intelligent vehicles, scalability and network availability [5], [6]. While MIVC systems are fraught with end-to-end communication delay, IVC systems generally have network partitioning problem in early deployment where the MPR is not sufficient to support the required connectivity among the vehicular nodes. This is because a minimum of two vehicular nodes equipped with smart computing devices within a communication range are necessary for communication in IVC systems. Furthermore, a significant improvement in MPR introduces scalability problem as the capacity of the shared medium reduces with growth in the connected vehicular nodes [20].

2.3.2 Infrastructure-Based Vehicular Communication System

The infrastructure-based vehicular networks have the presence of central infrastructures in form of access points (APs), RSUs or BSs to offer improved quality, resilience and reliability to the network. The communication here involves vehicle to RSU (V2R) or V2I, where the infrastructure provides the vehicles with access to online resources. The RSUs usually operate at a specific licensed frequency and at fixed locations along the motorway or urban road networks. They are located every 1 km or less to enable high data rate communication using cellular networks such as global system for mobile communication (GSM) and universal mobile telecommunications system (UMTS) [21]; and wireless local area network (WLAN). The fact that a pure V2V network as a standalone network cannot provide access to external online resources such as the Internet makes the infrastructure-based vehicular networks desirable, at least in some areas, to provide reliable broadband communication services, access to online resources and local services. Infrastructure-based vehicular communication systems provide a more reliable service than IVC systems in regions with low vehicular density where IVC systems cannot guarantee ubiquitous connectivity. The infrastructure based systems are categorised into sparse RVC (SRVC) and ubiquitous RVC (URVC) systems [19]. SRVC systems are deployed to provide communication services at hot spots such as a busy intersection scheduling traffic light, a gas station advertising prices and airport advertising parking spaces. A URVC system provides high-speed communication over the entire roadways. While the deployment SRVC system can be gradual and progressive with immediate benefits a substantial investment is required for providing a full or considerable coverage of roadways by URVC systems.

Effective utilisation of channel resources among the vehicles in this centralised communication system is enhanced by an efficient medium access control (MAC) protocol with signaling and coordination by the RSU or BS. The design and development of suitable and resilient MAC protocols therefore constitute a major research obligation in developing a viable vehicular communication network.

2.3.3 Hybrid Vehicular Communication Systems

In hybrid vehicular communication (HVC) systems, connectivity is provided by both the existing network infrastructure through a V2R protocol and traditional V2V networking [22]. HVC systems extend the service range of V2R systems by employing the RSUs to provide seamless connectivity when vehicles are of low density or travelling in disconnected neighbourhoods, and using V2V communications for dense traffic scenarios. Figure 2.3 shows a hybrid communication set up where vehicles outside the communication range of RSU can still access RSU online resources through neighbouring vehicles. The same applications in V2R systems are supported with greater transmission range by HVC systems.

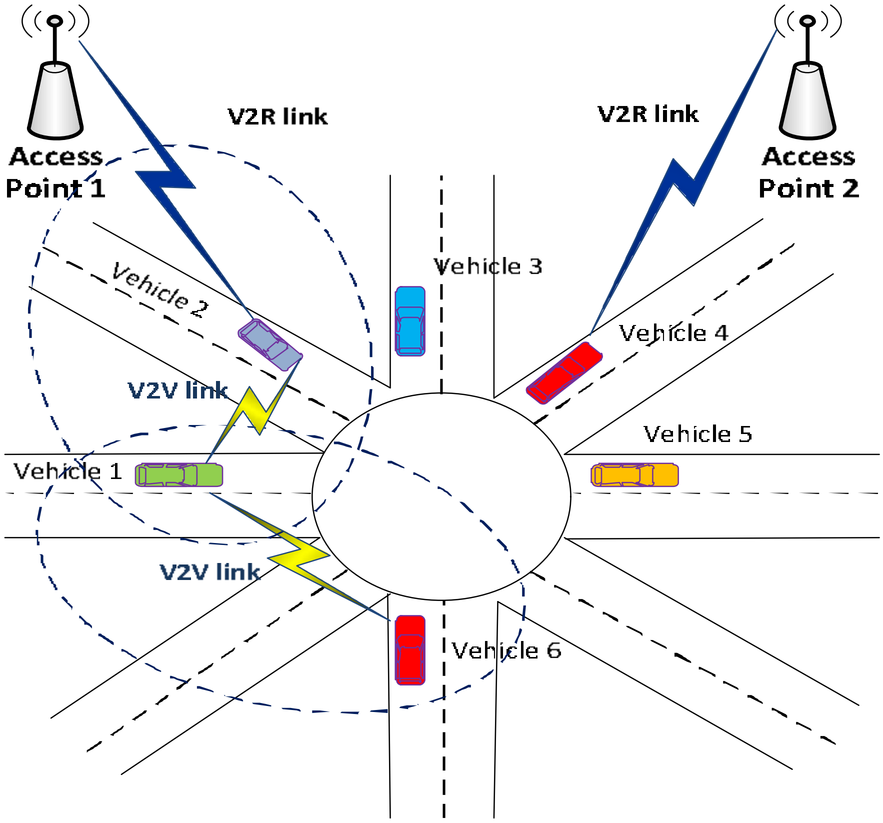

Figure 2.3: Hybrid vehicular communication system.

2.3.4 Vehicular Network Environments

The peculiar traffic, road network and environmental features associated with different vehicular network environments are important determinants of the nature of network infrastructures and communication protocols deployable in the areas. A singular network infrastructure pattern and communication protocol does not perform satisfactorily in different vehicular communication scenarios. The various existing network environments in which vehicular communication systems are deployed are divided into three categories: city or urban, motorway or highway and rural environments. The predictable restricted directional movement of vehicles in all the environments offers some design benefits to vehicular networks over other mobile communication networks that are associated with random unidirectional movement of devices. The huge drawback however lies in the wider range of coverage and high speed mobility that exist especially in the rural and motorways environments.

The wireless channel in city environment is faced with shadowing problem due to the obstructions from buildings and other structures [21]. High network congestion and the associated packet collisions are also rife in city environment during rush hours and at busy junctions. The traffic congestion can be lessened through effective traffic prediction that enables drivers to have journey plans with minimal congestions. The multiple wireless technologies which exist in urban environment however, offer the benefit of heterogeneous network deployment by utilising both cellular and Wi-Fi services for ubiquitous connectivity [6]. Conversely, the rural environment has sparse networks as only limited intelligent vehicles move on the road. Sparse resilient communication protocols are used while few infrastructures are deployed at hot spots and other areas of essential services for economic communications. The motorway environment has a hybrid communication system with an expansive coverage length associated with variable sparse and dense vehicular densities. The RSUs are located at regular intervals along the motorway stretch to provide ubiquitous connectivity with the support of V2V.

2.4 Vehicular Network Design Challenges

Vehicular networks differ from other kinds of mobile networks by their hybrid network architectures, highly mobile nodes, unreliable channel conditions and new application scenarios. These pose many unique research challenges to the design and development of an efficient vehicular network. The following are some of the challenges generally associated with vehicular networks [7], [15].

High mobility and rapidly changing topology: Vehicles generally move very fast especially on the highway causing rapid changes in the network topology. Many existing structures on effective data dissemination in the literature such as clustering, grid and tree are extremely difficult to set up and maintain. Because of the network diversity in both topology and mobility, vehicles stay in the communication range of each other just for several seconds, and links are formed and broken fast. Problems of frequent network disconnection and fragmentation are common in regions of low network density while the conventional broadcast based mechanism often leads to the problem of broadcast storm in areas of high density node network. Therefore, the routing protocols used in MANETs are hardly suitable for vehicular communications.

Hard delay constraints: Safety related applications of vehicular networks during emergency, accidents and hard brake events require on-time delivery of message to the appropriate node. Data delivery within the set maximum time is very crucial to the acceptable functionality of networks during such applications. Therefore high data rates are not as important an issue for vehicular networks as overcoming the issues of hard delay constraints where safety is the focus.

Mobility Modeling and Prediction: Driver's behaviour, mobility constraints and high speeds create unique characteristics that have implications on vehicular network architecture from the physical to application layers. This makes the characterisation of vehicular motion a difficult task. Cross-layer designs for vehicular networks therefore require an in-depth knowledge of the relation between vehicular mobility and network connectivity for a reliable and high performance network. Vehicular traffic flow theory focuses on two approaches, namely, macroscopic and microscopic, in the modeling of vehicular motion. Macroscopic approach views the flow of vehicles as fluid flow and adopts the existing fluid models, while microscopic approach attempts to characterise the movement of individual vehicle spatial models.

Communication Environment: Great variations exist between the mobility models of highways and that of a city environment. The node prediction design and routing algorithm also need to adapt to these variations. Highway mobility model, which is essentially a one-dimensional model, is rather simple and easy to predict, while city mobility model is very complex and difficult due to the street structure, variable node density, presence of buildings and trees that serve as obstacles to even small distance communication.

Efficient Channel Utilisation: Due to the high mobility of vehicles as well as frequently changing road conditions, the channel condition of a vehicular network is highly dynamic. The most commonly used methods for data dissemination in this network are broadcast and multicast which require large bandwidth consumption. This poses a performance challenge to the network with a limited bandwidth resource as a periodic transmission of safety messages by all vehicles in a dense traffic environment may cause severe network congestion. Broadcast packets are essential in vehicular networks both for route discovery and safety application messages propagation. Evolving a robust and effective transmission channel that addresses collision and broadcast storms issues is a challenge to vehicular network design.

Security and privacy: The accessibility of vehicular networks to all vehicles and road users makes it vulnerable to manifold attacks. The network security challenge boarders on protecting life-critical information from deformation, authenticating valid data and communicating nodes, and protecting the privacy of drivers.

2.5 Vehicular Network Technologies and Standards

Vehicular communication networks were allocated a special frequency band of 75 MHz at 5.9 GHz by the U.S. Federal Communication Commission (FCC) in 1999 to facilitate a short to medium (300 m to 1000 m) range communications between vehicles and the roadside infrastructures [23], [24]. This is aimed to provide safety to the road users as well as improving the efficiency of traffic flow. This initiative has been well followed by commendable efforts by the government, academia and industries to standardise the technologies and services of vehicular networks.

2.5.1 Dedicated Short Range Communications (DSRC)

DSRC is a short to medium range communications service developed primarily to support communications-based active safety applications of ITS. It operates over a dedicated 75 MHz spectrum band at 5.9 GHz allocated in 1999 by United States FCC to provide the tightly controlled spectrum requirement by Communications-based active safety systems for reliable service. Following the spectrum band allocation, the American Society for Testing and Materials (ASTM) in 2003, approved the ASTM-DSRC standard which was based on the IEEE802.11a physical layer and 802.11 MAC layer [7], [23]. This standard was later published as ASTM E2213-03. The service and licensing rules that govern the use of the DSRC band were established in February 2004 by the report issued by the FCC. The choice of DSRC over Wi-Fi is for the purpose of avoiding an intolerable and uncontrollable level of interference that could hamper the reliability and effectiveness of active safety applications based on the proliferation of Wi-Fi hand-held and hands-free devices that occupy the 2.4 GHz and 5 GHz bands, along with the projected increase in Wi-Fi hot spots and wireless mesh extensions [25]. DSRC is free but operates in a licensed frequency band. It supports both V2V and V2I communications by providing a secure wireless interface required by active safety applications. The primary aim of DSRC is to provide high data transfers and low communication latency in small communication zones. It has desirable qualities such as low latency, fast network acquisition provisioning, high reliability, priority service provisioning for safety applications, interoperability and provisioning of safety message authentication and privacy [26]. The range of applications covered by these communication services includes V2V safety messages, traffic information, toll collection, infotainments, and several others. The DSRC spectrum is divided into 7 channels with each having a bandwidth of 10 MHz as opposed to the 20 MHz IEEE 802.11a channel bandwidth. The smaller bandwidth channels of DSRC offer improved wireless channel propagation with respect to multi-path delay spread and Doppler effects in roadway environments. One of the channels is dedicated solely for safety communications while two others are reserved for future critical safety applications. The remaining channels which are service channels are used for either safety or non-safety applications with safety applications accorded higher priority [27]. Europe and Japan also have their standards for DSRC with slight differences in frequency allocations.

2.5.2 Wireless Access in Vehicular Environments (WAVE)

In order to define the architecture and standardised set of services and interfaces that ensure a secured V2V and V2I wireless communications, the ASTM 2313 working group moved to the IEEE 802.11 standard group and renamed the DSRC as IEEE 802.11p Wireless Access in Vehicular Environments (WAVE) [28]. By the incorporation of DSRC into IEEE 802.11, the WAVE family of standards became universally accepted standards in contrast to the different regional standards of DSRC by Europe, Japan and America. The RSU and the OBU which are fixed and mobile devices respectively are the two types of devices whose functionalities are defined by WAVE standards. The WAVE standard stack consists of IEEE 802.11p standard which deals with the physical and MAC layers of vehicular communication, and IEEE 1609 standards which stipulate other higher-layer protocols [29].

2.5.2.1 IEEE 802.11p Standards for WAVE

The IEEE 802.11p draft is an amendment of 802.11 standard intended for new classes of applications to be used in a vehicular environment. These include road safety and emergency services which require high reliability and low latency. The PHY layer of 802.11p adopts 802.11a with the modification of certain parameters such as symbol clock frequency tolerance, transmit centre frequency tolerance, operating temperature, adjacent/non-adjacent channel rejection, receiver minimum input sensitivity etc. The 802.11p PHY uses 10 MHz channels with transfer rates of 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps compared to 20 MHz channels used by 802.11a. In 802.11p PHY, Orthogonal Frequency Division Multiplexing (OFDM) is used as transmission technique to divide the available frequency spectrum into narrower sub-channels (subcarriers). The high-rate data stream is split into a number of lower-rate data streams transmitted simultaneously over a number of subcarriers, where each subcarrier is narrow banded. OFDM offers the benefit of better handling of frequency selective fading than a single-carrier system, hence, avoiding the situation of a single fade or interferer breaking an entire link [30].

The MAC layer of 802.11p uses the enhanced distributed channel access (EDCA) derived from the IEEE 802.11e. This provides prioritised access to the channel by using queues with different arbitration inter-frame spaces (AIFS). Each terminal in an 802.11p network has queues with different priorities with the queue having the highest priority waiting for the shortest period of time (shortest AIFS) before starting transmission. By this way, different priorities are enforced, and stations having low priority traffic lose the race for the channel when competing with stations with higher priority traffic [7].

2.5.2.2 IEEE 1609 Standards for WAVE

It is worth noting that IEEE 802.11p is limited by the scope of IEEE 802.11 which strictly works at the media access control and physical layers [7]. The operational functions and complexity related to DSRC are handled by the upper layers of the IEEE 1609 standards. These standards define how applications that utilise WAVE will function in the WAVE environment. They reside above 802.11p and support the operation of higher layers without the need to deal with the physical channel access parameters.

- IEEE 1609.1 Resource Manager describes the wireless access method in WAVE environment and allows remote applications located outside the vehicular environment to establish connection with WAVE enabled vehicles [31].

- IEEE 1609.2 Security Services describe various secure message patterns to process messages for WAVE systems. This standard addresses security methods for WAVE management messages and application messages that ensure security against eavesdropping, spoofing and information linkage to unauthorised parties [32].
- IEEE 1609.3 Networking Services define network and transport layer services such as addressing and routing to enhance secure WAVE data exchange. It supports both Wave Short Messages (WSM) services and to IPv6 (Internet Protocol version 6) [33].
- IEEE 1609.4 Multi-Channel Operations offers enhancements to the IEEE 802.11 MAC to support WAVE operation by describing the various standard message formats for DSRC applications [34].

2.6 Medium Access Control (MAC) Protocols in Vehicular Communications

Every communication system has a protocol stack which is more or less complex depending on the task of the communication system. The MAC layer is a sublayer of the data link layer of the OSI reference protocol stack [35], and it is present in most communication networks; wired as well as wireless. The MAC protocol has the responsibility of determining which terminal has the right to transmit on the communication channel at any given time. This is due to the fact that the limited bandwidth resource has many devices or nodes that may want to access it at the same time, which can lead to collisions and thereby disrupting the network performance. Myriads of MAC protocols have been designed for the purpose of enhancing effective transmission of data over a shared communication medium in both wired and wireless networks. Different network scenarios and features dictate the choice of appropriate MAC protocol that suits its requirements and applications. For this reason, most of the MAC protocols that deliver high QoS and throughput in MANETs cannot be used in vehicular networks because of their poor and unsatisfactory performance.

The peculiar features of vehicular networks such as high mobility of vehicles, predetermined direction of motion according to road topology, limited support of road side infrastructures, stringent delivery time requirement of critical messages, and few vehicles forming independent ad hoc network in an RSU region, necessitate that some characteristic-based design precautions be observed in vehicular network MAC protocols to achieve desirable QoS. Firstly, vehicles move in and out of the RSU coverage region with high speeds and in predetermined directional roadways in short intervals of time, hence, the vehicles have a short stay period in each RSU region and with density varying from sparse to dense. The MAC protocol that captures these features should therefore be distributed or have minimal reliance on RSU with an efficient handoff mechanism from one RSU to another. Secondly, the confinement of vehicles movement to the roadways encourage the use of directional antennas which offer the advantages of reduced interference, increased spectrum reuse, and reduced power consumption. Thirdly, the broadcasting nature of most communications in vehicular networks over the shared wireless channel makes it highly liable to contention delay. It is necessary therefore that protocols ensure that time bound safety critical messages are delivered within their set period of relevance. The hidden and exposed terminal problems should be minimised. Fourthly, the variableness of vehicles density in RSU regions requires a scalable and bandwidth efficient MAC. Lastly, power control mechanisms and adaptive data rate control are needed for efficient management of the energy consumption of the nodes [36], [37].

2.6.1 Contention Based and Contention-Free Protocols

The MAC protocols can be broadly classified into two categories: contention based and conflict-free protocols. Conflict-free protocols ensure that a transmission is not interfered by any other transmissions, i.e., no overlap occurs in time, frequency, or space between transmitters and therefore the possibility of collisions occurrence is eliminated. Time division multiple access (TDMA) and frequency division multiple access (FDMA) are chief examples of conflict-free protocols [38], [39]. TDMA involves the division of transmission period into time slots, such that each transmitting node in the network has the exclusive right of using the total available frequency spectrum for transmission within a time slot. It has the disadvantage of allowing idle slot(s) if a terminal has nothing to send while other terminals (users) may have packets waiting to be transmitted. FDMA, on the other hand, involves the division of the frequency band into narrower subchannels such that each user is allotted a subchannel to enable it to transmit at any point in time using its subchannel. The use of FDMA has a drawback of inefficient utilisation of bandwidth resource when the traffic is bursty. However, a combination of TDMA and FDMA finds application in systems with a centralised network topology such as a GSM mobile system [39]. The above named conflict free protocols require a centralised resource management infrastructure such as a base station or an access point for the allocation of time and frequency resources among the terminals. In a centralised wireless network, communication between nodes is through the BS where the uplinks are one last-hop links between the nodes and BS and the downlinks can be broadcast to all nodes. The downlink broadcast from the BS to all the nodes within its coverage eliminates the problems of hidden and exposed nodes in centralised architecture. This is however unsuitable for a decentralised mobile network system like pure V2V network.

Conversely, contention based MAC protocols do not offer users an exclusive right to transmit using the assigned resources in a predetermined way. Instead, various nodes compete for the right of using the shared medium resources with the attendant possibility of collisions. They however provide mechanisms for addressing collision occurrences in order to achieve packets transmission with acceptable QoS [40]. The contention based MAC protocols usually function in distributed or ad-hoc networks without a centralised coordinator. Communication is directly by the nodes through multi-hop between the source and destination. The absence of central coordination in assigning frequencies to the various nodes, however, restricts the network to a single operating frequency band that allows only one node to transmit at a time. Collision occurs when more than one node attempt transmitting at a time. The two large groups of contention based protocols are Aloha and CSMA (Carrier sense multiple access) [41]. In the simplest Aloha protocol, each transmitter sends its packet as soon as it is locally generated. CSMA is an improved Aloha protocol where the transmitter starts by sensing the channel before the transmission is initiated and only transmits if the channel is free, i.e., “listen before talk.” In order to reduce the probability that several transmitters start sending immediately when the channel becomes free, each transmitter randomises a backoff time during which it defers channel access. These two protocols are very popular, since they are easily deployed. The drawback is the possibility of two or more transmissions colliding and continuing to collide indefinitely, hence resulting in packets suffering unbounded delays. This drawback is especially severe in a real-time system intended for traffic safety applications where satisfying a worst case access time condition is crucial.

2.6.2 Classification Of MAC Protocols In Vehicular Networks

Many MAC protocols have been proposed for different communication applications, ranging from wired, fixed wireless, mobile ad hoc to vehicular ad hoc network system. MAC protocols are generally classified according to the functions they perform and/or the mechanisms employed in their operations. The major classes of MAC protocols are as follows.

2.6.2.1 IEEE 802.11 MAC (CSMA/CA)

IEEE 802.11 is a wireless communication standard that can operate in two modes: centralised mode where mobile nodes communicate with APs, and ad hoc mode where mobile nodes communicate with one another directly without using any infrastructure [42]. The choice of IEEE 802.11 standard is largely due to its wide acceptance by the network community as a standard in wireless communications, and the acceptable compatibility it has with the existing inexpensive devices [42]. IEEE 802.11 standard uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol at MAC layer. In order to prevent collisions in the network, the network nodes listen to the shared medium to confirm if it is in use or reserved before transmitting. The two carrier sensing techniques usually employed are the physical and virtual carrier sensing methods. The physical carrier sensing is dependent upon the physical layer and the hardware used, and disadvantageous in the sense that the hidden terminals cannot be heard physically. The virtual carrier sensing, uses a Network Allocation Vector (NAV) to determine the duration for which the channel will be busy. It is accomplished through the use of Request-To-Send (RTS) and Clear-To-Send (CTS) control packets. This procedure (RTS-CTS-Data-ACK) is called the Distributed Coordination Function (DCF) [43].

In order to properly manage the medium access process, some important interval spaces, called Inter-Frame Spacings (IFS), are set between two successive transmission frames [42], [43]. For instance each vehicle first senses the medium state before attempting transmission. The vehicle transmits if the medium is sensed to be idle for certain duration of time called Distributed IFS (DIFS) or backs off and attempts again after a period of time within the contention window (CW). When a vehicle wants to transmit, it broadcasts an RTS packet which includes its ID and the expected duration of the transmission if the medium is sensed to be idle. On receiving this packet all nodes set their NAV accordingly to keep track of the medium busy duration. If the receiver is in a position to receive the data packet, it replies by sending a CTS packet which also includes the transmission duration time. All neighbours once again set their NAV accordingly on receiving the CTS packet to show their awareness of the ongoing transmission. When the sending vehicle receives the CTS, it waits for Short IFS (SIFS) time before commencing the data transmission. The receiver, after successfully receiving the data frame, waits again for a SIFS time and sends an ACK packet only to the sender. By this technique the hidden terminal issue is resolved while the risk of transmission collisions is minimized.

2.6.2.2 ADHOC MAC

ADHOC MAC, a protocol developed by the European project CarTALK 2000, has been proposed to overcome the issues facing vehicular networks and provide a reliable broadcast service that overcomes hidden and exposed node problems. In contrast to 802.11 standard, ADHOC MAC is based on a dynamic TDMA mechanism and employs UMTS Terrestrial Radio Access Time Division Duplex (UTRA-TDD) as the physical layer. ADHOC MAC uses Reliable Reservation-ALOHA (RR-ALOHA) which is an extended version of

Reservation-ALOHA (R-ALOHA) protocol. As in all cases of TDMA based protocols, the medium is partitioned into several repeated time frames of which each is divided into N time slots. Each vehicle that wants to send data needs to first reserve for itself one basic channel (BCH), which is one of the periodically repeated time slots in successive frames.

Reservation Aloha works similar to Slotted-Aloha in the sense of a random access used to transmit in an available slot. The reservation ability however allows a node to continue transmitting in the same slot in subsequent frames without contention. This reservation procedure fundamentally requires a central repeater to relay reservations so that all nodes maintain the same slot status information in order to avoid collisions. Shifting this centralized procedure to an ad-hoc environment resulted in the proposal of RR-ALOHA. The RR-ALOHA solves the problem of slot status information by introducing the periodic dissemination of Frame Information (FI) by all nodes in their slot periods. The FI is a vector with N entries specifying the status of the N previous slots as perceived by the node. A node simply marks a slot as busy along with the transmitting nodes ID if it has successfully transmitted or received packets in that slot. With the diffusion of FI all nodes within the two-hop network are aware of reserved slots allowing the network to avoid hidden and exposed node problems. Disjoint one-hop clusters on the other hand view different slot information allowing a slot reuse in different coverage areas. The FI also enables nodes joining the network to listen to a time frame for all other member node FI broadcasts before attempting to reserve a slot [44], [45].

2.6.2.3 Directional Antenna-Based MAC Protocols

The use of a directional antennas in ad hoc networks offers the benefit of having a directional and concentrated signal transmission that makes for a better reception at the receiving terminal. This technology demands that the space around the terminal be divided into N transmission angles of (360/N) degrees [42]. This approach helps in reducing transmission collisions and provides increased possibility of channel reuse. Since the movement of vehicles in vehicular networks is according to the road topology and driving rules, directional antenna transmission reduces interference and collisions associated with the parallel opposite traffics. Signal to interference and noise ratio (SINR) can be greatly improved if the transmitting and receiving nodes use selective directions that exclude interferences of unwanted directions. The higher gain of directional antennas also improves the communication range of the nodes, making it possible to send messages to distant nodes in fewer hops [46]. Different directional antenna schemes have been proposed to include a single antenna that can be rotated or multiple antennas facing different directions.

A Directional MAC (D-MAC) protocol is proposed in [47] with the requirement that each terminal has knowledge of its geographical position and that of its neighbours, by using positioning systems such as GPS. D-MAC protocol employs RTS/CTS/ACK handshake method being based on the IEEE 802.11. A directional antenna becomes blocked when it receives a RTS or CTS packet and does not interfere with the neighbour’s transmission for the specified transmission duration time of the packet. Hence, the hidden terminal problem and transmission collisions are greatly minimized by D-MAC protocol while the exposed terminal problem is not addressed. The complexity associated with the real implementation and management of directional antennas in vehicular networks however, makes it difficult to harness its promising network performance improvement.

2.6.2.4 Multiple Channel MAC protocols

Multiple channel MAC protocols are designed to address high transmission collision probability associated with single channel schemes with large number of nodes. Multiple channel schemes are broadly classified into two according to [48]. These include schemes that use a dedicated channel for control packets and one separate channel for data transmissions, and others which employ multiple channels for data transmission. In the first category, busy tones of small bandwidth are set up in the control channel to inform the nodes about the ongoing transmissions. The use of multiple channels in both cases offer the benefits of enhancing multiple transmissions in the same region, increasing throughput, reducing interference and QoS improvement. The difficulty associated with the real time implementation of multiple channel schemes, especially, allotting the time slots when nodes would access the channels is underscored in [48]. The authors in [49] have also categorised multiple channel protocols into single rendezvous and parallel rendezvous protocols based on the number of control channels used for signalling. In single rendezvous protocols, a single channel is used at any time for the exchange of control information among nodes, though the channel may be changed over time. Multiple nodes use different channels in parallel for the control information exchange in parallel rendezvous protocols. While parallel rendezvous protocols lessen the congestion problem of single rendezvous protocol, channels allotment to the nodes still poses a challenge. A more detailed classification based on the general principles of operation of multiple channel protocols is presented in [49]. The classes include dedicated control channel, common hopping, split phase, and multiple arrangement methods. In dedicated control channel protocols, every node has two radios of which one is dedicated to a control channel for control messages exchange while the other radio is tuned to any other data channel. The common hopping approach has improvement over dedicated control channel for each device having only one transceiver and using all channels for data exchange. The idle nodes synchronously hop through all channels and only stop when a pair of nodes have transmission agreement. The split phase approach devices also use a single radio with the time being divided into an alternating sequence of control and data phases. All nodes have to tune to the control channel during a control phase to make transmission agreements. In the multiple arrangement technique multiple pairs of devices can make transmission agreements on distinct channels.

2.6.2.5 Power-Aware MAC Protocols

Effective utilisation of energy is crucial in communication systems as many network devices are often battery power driven. Power-aware MAC protocols are beneficial in respect of minimising network power consumption and improving spatial frequency reuse. The guiding principles for the design of energy efficient MAC include 1) avoidance of collisions which usually necessitate energy intensive retransmissions, 2) keeping the transceivers, which have the highest level of energy consumption when in active state, in standby or switched off mode when idle, and 3) providing effective power control mechanism to ensure transmitters transmit at lower power mode that is sufficient to effect successful transmission, rather than maximum power mode that engenders high interference with neighbouring transmitters. Hence, the low interference level occasioned by the transmission power control improves the space-time utilisation efficiency since reducing the transmit power permits more nodes to communicate concurrently [50]. Some power control protocols vary the transmitting power according to the packet size to avoid having to expend more energy in retransmissions due to packet delivery errors that arise from insufficient transmit power while trying to save energy.

In power-control MAC (PCM) the RTS and CTS packets are transmitted at maximum power while the data and ACK packets are sent at the minimum possible power determined from RTS-CTS handshake procedure. Other power control MAC protocols include Power-Controlled Multiple Access (PCMA), Dynamic Power-Saving Mechanism (DPSM) and Power-Aware Medium Access Control with Signaling (PAMAS) [48]. PCMA relies on controlling the transmission power of the source node with the condition that the intended receiver is able to receive the packet. This approach prevents interference with neighboring devices that are not involved in the ongoing communication. DPSM employs the concept of switching nodes dynamically to sleep and wake modes to minimise power consumption, while PAMAS has different power levels for RTS-CTS interactions over the control channel and the data transmissions over a data channel.

2.7 Energy Efficiency in Wireless Network

In recent years, the networking research community has shown a growing interest in exploring energy-efficient techniques for wireless networks. The need to effectively manage energy in wireless networks is necessitated by the energy constraints of the connected devices. Since most of these devices are powered by batteries which possess limited energy density, efficient energy utilisation of the devices is very vital to enhancing the network lifetime. Other compelling reasons for energy efficient wireless networks include economy and environmental reasons. With the current number of 3G and 4G BSs in the UK exceeding 12000 [51], about 50 GWh is expended in a year. This invariably leads to not only significant carbon emissions but also much higher operating costs for telecoms providers. In terms of the global carbon emissions, it is reported that information and communication technology (ICT) accounts for 2–2.5% of all harmful emissions [9]. According to [52], approximately 3% or 600 TWh of the worldwide electrical energy is consumed by the ICT sector, and it is estimated that energy consumption for ICT will grow to 1,700 TWh by 2030 [52].

Fixed infrastructure networks usually contain one or more centralised nodes such as APs or BSs, which are connected to the Internet backbone. In these networks, there is no peer-to-peer communication between the mobile nodes; each node communicates directly with the BS or AP which performs the main networking and control functions. Nodes in wireless ad hoc networks can communicate in peer-to-peer mode and perform some distributed networking and control functions. When the nodes are out of the communication range of each other, intermediate nodes are used as relays to enable their communication through multi-hop routing [9]. One major factor that accounts for energy consumption in wireless networks is the functional state of the connected devices. The four states in which the devices are classified in the parlance of energy consumption are transmitting, receiving, listening and sleeping states. While a substantial amount of power is consumed in the transmitting and receiving states, devices in listening state have low power consumption. According to the authors in [53] and [54], the power consumption ratios of listening, receiving and transmitting states are 1:1.05:1.4 and 1:1.2:1.7 respectively. Based on the significant amount of energy that can be saved by putting as many nodes as possible into sleeping state while maintaining an acceptable QoS, several authors have proposed various sleep strategies for achieving energy efficiency in wireless networks [14], [55]. The approaches that rely on switching off the transmitting circuitry in order to set the transceiver into low energy state are jointly grouped under sleep [56]. The authors in [57], [58] introduced a packet-driven sleep and wake-up modes which offer an energy saving of about 60% in comparison to the normal IEEE 802.11 power save mechanism (PSM). In [59], a multi-frequency wake-up mechanism placing nodes on different sleeping durations is proposed. A traffic shaping protocol which prolongs sleep durations of the nodes is proposed in [60] to enhance the performance of normal PSM. The approach in [60] saves 83% energy compared to normal PSM.

Single-hop communication (SHC) in wireless networks is concerned with direct communication between the source and destination nodes, while intermediary nodes are employed to relay or forward the message from one node to another until the destination node is reached in multi-hop communication (MHC). The energy consumption in SHC is according to the maximum transmission range, and this fixed transmission distance amounts to waste of energy where communication is between two close nodes. The total energy consumed in MHC varies according to the number of intermediary nodes and the energy consumed in each hop, which varies with the transmission distance. The power consumption of a node for transmission is divided into two parts which include power consumed in electronic circuitry and power consumed by output amplifier. During signal reception, the power consumption is due mainly to the receiving node's electronic circuitry. Hence, power saving can be achieved through approaches that optimise the transmit power levels at the source nodes during transmission activities. The application of transmission range adjustment to reduce the energy has been analysed by several authors. In [61] an RF output power optimisation technique is employed to enhance energy savings. The achieved results indicate that a significant amount of power can be saved with MHC as compared to direct communication from a source to the BS. The authors in [61] use similar strategy to save energy in a centralised network. However, the author in [62] contends that the optimisation of RF transmit power offers but little saving as power consumption by the transmitter circuitry such as frequency synthesisers is much higher than the transmitter output power. Joint energy savings can nevertheless be obtained with reduced transmission power and optimised operational power. An energy efficient cluster-based scheme, called low-energy adaptive clustering hierarchy (LEACH) is proposed in [63], where energy load is uniformly distributed among the participating nodes of the network through randomised rotation of local cluster heads.

2.7.1 Energy Efficiency in Vehicular Network

Several research efforts have in recent past focused on energy-efficiency in vehicular networks. Although the vehicle on-board devices are not energy constrained as they derive energy from vehicle batteries, the communications in vehicular networks however involve other devices which rely on renewable energy sources for their operations. In order to improve power and resource allocation efficiency in vehicular networks, the authors in [64] proposed a cross layer optimisation framework, based on a joint power and sub-carrier assignment policy. While taking the delay QoS requirements of each vehicle into account, a joint power and sub-carrier assignment policy was derived to improve power efficiency in V2R network, with the primary objective of minimising the overall power consumption by the proposed scheme while satisfying the given effective bandwidth constraints; the obtained experimental results prove that the proposed policy performs better than the other existing resource allocation policies.

In [65], cooperative techniques which are based on the multi-hop, cooperative relay, and cooperative multiple input and multiple output (MIMO) techniques, have been proposed to enhance energy-efficient transmissions between the road infrastructures and vehicles. The techniques exploit the transmission diversity gain to improve the performance or reduce the transmission energy consumption of the system. The authors in [61] employ cooperative relaying where messages are forwarded to a BS with the help of vehicular relay nodes to improve the energy efficiency of the network. In [61] an RF output power optimisation technique is employed to enhance energy savings. The achieved results indicate that a significant amount of power can be saved with MHC as compared to direct communication from a source to the BS which requires power for fixed maximum transmission range at all times. Hammad et al. [66] developed a time-slot-based BS scheduling scheme to minimise the energy consumption of downlink infrastructure-to-vehicle communication. The scheme works by delaying message transmission from the RSU to vehicle until the vehicle comes close to the RSU since lesser power is required to communicate with a closer node than a more distant one. As soon as a vehicle enters the coverage area of an RSU, it sends its speed and current position to the RSU and the RSU uses this information to determine its downlink transmission parameters.

The authors in [9] applied Geographical Adaptive Fidelity (GAF), one of the topology management protocols, to manage the states of network nodes and select the multi-hop relay nodes that can improve energy efficiency based on vehicular nodes' position information. The cluster based scheme rely on minimising the number of nodes involved in relaying by dividing the motorway stretch into equal-grids and adjustable-grids, where each grid has one or more optimal set of active nodes to form the network backbone, while other grid members which are not transmitting or relaying packets go to sleep to save more energy. The performance evaluation of various grid schemes in terms of energy savings reveal that the genetic algorithm based grid model outperform both the equal-grid and adjustable-grid models.

The type of routing protocol deployed in a network affects the energy dynamics of the nodes in a number of ways. The routing network load affects the amount of energy used in sending and receiving routing control messages, and the generated routing paths affect the energy required by the source node to forward data packets to the receiving nodes. In addition, the energy conservation techniques applied in vehicular networks communications must not jeopardise the real-time transmissions that satisfy strict delay aware requirements [67]. In [68], a clustering scheme known as a double cluster-head (DCH) scheme is proposed which considers mobility in selecting cluster-heads and saves energy through random sleep cycles while taking traffic into account and maintaining the required QoS. The authors used real vehicular and data traffic measurements to evaluate the performance of the DCH scheme which was compared with the existing single cluster-head (SCH) scheme. The results show a significant energy saving. The QoS optimised link state routing (OLSR) protocol was studied in [69], [70] using Differential Evolution (DE). In [70] a DE algorithm is employed to search for energy-efficient configurations that reduce the energy consumption of the OLSR protocol in vehicular networks. The authors' result proves that significant improvements over the standard configuration can be attained in terms of energy savings (up to 30%) without degrading the QoS. A Monte Carlo method and DE algorithm are used in [71] to search for energy efficient ad hoc on demand vector (AODV) configurations for VANETS.

The authors in [55] propose a dynamic switching activity for a BS when in low traffic conditions to save energy. This strategy is rather unsuitable for a BS-only scenario considering the transient nature of vehicular traffics and the high resource activation time and overhead that may result from the ping-pong effect of rapid dynamic switching the BS on and off [72]. This architecture is hence unfit for vehicular networks. A periodic sleep scheme for cellular networks is investigated in [73] with the authors achieving about 46% saving in operating energy expenditure. The proposed architecture which utilises a cell breathing scheme is however a multi-layered type which incurs high overhead that cannot be tolerated in a highly mobile network with fast changing traffic demand, as in a motorway communication environment. A promising solution to this architectural challenge is the deployment of a heterogeneous macro-micro cellular structure, where micro-cells/pico-cells served by APs/RSUs that support higher data rates are deployed within a macro-cell served by a BS [3]. The overall energy consumption of the network can be improved by putting the APs/RSUs to sleep when they are inactive.

2.8 Queuing Theory Based Analysis

Queuing theory is a vital analytical tool used extensively in the modelling of communication network problems and scenarios [74]. Although queueing theory based models have wide range of applications in the QoS predictions of access networks [75], vehicular communication networks only have limited consideration. The authors in [76] evaluated the QoS parameters, such as throughput, packet blocking probability and end-to-end delay using queuing models. A generic model to optimise the buffer size while maintaining the throughput above a certain threshold is proposed in [77] based on [76]. The authors in [3] investigated two types of random vacations, namely queue length independent vacations and queue length dependent vacations. While the queue length independent vacations are used to model wireless channel impairments, the queue length dependent vacations are used to model queue length dependent sleep cycles. The packet arrival process and the service discipline were both assumed to follow an exponential distribution. The two vacation cases studied are therefore modelled as M/M/c and M/M/1/K queues with random vacations. The Markov chain representations of the queue models were solved using the Matrix Geometric Method (MGM).

A queuing analytical framework which integrates vacation queuing and priority queuing is proposed in [78] in terms of QoS and energy efficiency the performance of a multi-hop relay network. The sleep cycle of the node is captured by the vacation queuing model while the priority queuing model is formed to differentiate between source packets and relayed packets at the node. The performances of an energy-aware S-ALOHA and 802.11 DCF MAC protocols are evaluated while investigating the trade-off between energy savings and QoS parameters using the proposed framework. A queuing theory based model is developed in [79] for performance analysis of radio link level in a multirate orthogonal frequency-division multiple access (OFDMA) network with adaptive fair rate allocation in terms of packet transmission delay and packet dropping probability. The obtained simulation and analytic results prove that the proposed framework can be used for the design and performance analysis of multirate and multiuser OFDMA networks. In [80], an M/M/1 queuing model is presented to study the performance of a collision warning protocol where the key performance metrics evaluated are the warning messages delay and throughput. With service rate being an important performance parameter of emerging communication networks, a methodology that utilises an M/M/1 queue to model vehicular traffic parameters of a road intersection for the service rate optimisation is presented in [81].

The authors in [68] model the performance of a cluster head (CH) with random sleep cycles in a V2V communication scenario as an M/M/1/K queue with random queue length dependence. While energy efficiency is enhanced and the packet blocking probability maintained within acceptable bounds, the average packet delay however, attains an unacceptable level for audio conferencing applications [68], though suitable for video conferencing applications. The frequent switching of the server (AP/RSU) to sleep by the proposed sleep strategy can degrade system performance at low load conditions [3], which leads to high average packet delay [68]. Hence, a better sleep strategy such as reactive sleep cycles, can be utilized for improved QoS. The authors in [82] investigate the feasibility of vacant UHF TV spectrum deployment for vehicular access networks by modelling the vacant TV channels as a multiserver, multipriority, preemptive queues. The performance evaluation of the models which are denoted as M/M/c and M/G/c queues prove the feasibility of vehicular communications in rural and suburban areas using this free spectrum while satisfying the QoS requirement of DSRC. This scheme can also be extended to vehicular communications in urban areas.

2.9 Renewable Energy in Vehicular Networks

Provisioning of ubiquitous connectivity with acceptable QoS in vehicular communication systems is fraught with enormous challenges posed by the dynamic and off-grid environment in which the network operates. These fundamental challenges are further compounded by the global cry for the carbon footprint mitigation. Hence, any outdoor wireless systems that would provide good coverage are inevitably faced with both high economic and environmental issues to address. This is especially due to the reliance of the dispersed network infrastructures (BSs and Aps/RSUs) on the power grid which may not be economically feasible to be deployed to roadways such as sparse rural and motorway communication environments. Several BS optimization techniques aimed at mitigating the environmental issues pertinent to the surging telecommunication industry have been investigated [14], [83]. These are basically efficient deployment strategies which rely on utilising energy aware components and load adaptive hardware and software modules to minimise power consumption and the associated carbon footprint. The option however that offers both economic and environmental benefits is the deployment of renewable energy sources such as wind or solar power [84]. Deployment of RSUs or BSs powered with renewable energy sources in a standalone fashion reduces the carbon footprint as well as alleviating the common issues associated with grid connected renewable energy farms, while providing ease of operation (deployment and maintenance) in remote areas such as countryside and motorways. Such deployments also eliminate several power systems related issues such as distribution, metering and grid maintenance. With the renewable power generation technologies becoming increasingly cost-competitive, and the option of off-grid electrification in most areas and locations with good resources becoming more economic [12], the renewable energy sources in conjunction with fast rechargeable batteries have become an attractive option to power the BSs/RSUs in sparse vehicular environments. By this scheme, the high cost of extending the national grid lines which would be grossly underutilised to the isolated roadway locations of vehicular networks can be avoided. Furthermore, reliance on the prevalent option of deploying diesel generators which have a multiplying effect on the operational cost while compounding the carbon emission dilemma, can equally be avoided [11].

Substantial research efforts have been directed towards limiting the energy consumption of wireless communications infrastructures and devices through several energy efficient techniques in order to bring the energy consumption to the level that can be effectively supplied by the renewable energy sources for the dual benefits of economy and improved environmental condition. The number of high power BSs in VCN is reduced by deploying pico-cells served by low power RSUs within a macro cell that is served by the BS intermittently. This heterogeneous network offers high data rates and reduces number of BSs while satisfying the QoS criteria [14]. Small size standalone renewable energy systems which have benefits of low cost, easy and large scale deployments can be implemented for these low power RSUs. While considerable research bordering on energy efficiency in wireless and sensor networks have been undertaken, only very little work has considered efficient utilisation of renewable energy sources. The work in [85] considered the improvement of energy efficiency in a renewable energy powered wireless communication system. The authors in [85] presented optimal scheduling algorithms for data transmission at different rates in order to maximise throughput under given time limits and energy constraints. The energy consumption analysis carried out was based on a one-transmitter multiple-receiver system.

Global environmental concerns inherent in conventional energy generation have led to increased development of renewable alternative energy sources in power systems. Many nations across the globe have set high wind penetration targets in their energy generation mix to mitigate the greenhouse effect arising from the conventional generations. In terms of the global carbon emissions, it is reported that information and communication technology (ICT) accounts for 2–2.5% of all harmful emissions [9]. The “Green Power for Mobile” initiative promises to cut down carbon emissions by about 6.8 million tons and save up to 2.5 billion litres of fuel with target of 118,000 renewable energy powered BSs [11]. Greening communication networks can be realised by employing energy efficient protocols and technologies that minimise the network power consumption. The carbon foot print can be further reduced by replacing the conventional energy sources with renewable energy sources that are capable of delivering the system power demand. The sun is one good renewable energy source that can be utilised in this regard. The sun can deliver to the earth surface in one hour about 1.2×10^{11} MWh of energy, which is equivalent to the total amount of energy consumed in one year by humans [86]. Solar energy has been employed in several places to power wireless networks. In 2008, 76% of the total number of renewable energy source powered BSs by China Mobile were solar powered while the remaining 24% were hybrid (solar and wind) powered [86]. The Green Wi-Fi initiative partnered with Inveneo to provide solar powered internet connectivity for developing countries [87]. Several solar powered mesh networks have also been deployed in America and some developing nations [88]. While most of the networks powered solely by solar energy only function in the day time when solar irradiation is available, vehicular networks are required to function both day and night according to the real vehicular data measurements. Moreover, the deployment of standalone solar powered RSU in geographical locations with low solar irradiations such as the UK would require larger battery storage and photovoltaic arrays to guarantee steady power supply at all times [89].

Another renewable energy source that has enjoyed wide deployments both in small and large scales is wind energy. The feasibility of small scale deployment of wind energy in what is termed small standalone wind energy conversion systems (SSWECS) for rural residents usage has been well explored in developing countries [90]. The residential loads in the rural areas were to assess the viability of SSWECS by comparing the simulated generating capacity of the energy system with the energy demand. However, the viability assessment of wind energy systems in the parlance of a rural residential setting cannot guarantee the stringent QoS requirements of telecommunication network applications which include vehicular communication networks. The intermittent nature of renewable energy resources (such as wind and solar energy sources) has led to the need of incorporating energy storage devices such as fast rechargeable batteries. While there is no control over wind power availability, its usage at any time is controllable when a suitable battery is used [91]. Although the previous works underscore the imperative of appending storage systems to the generated wind energy, their emphasis is limited to large amounts of energy without concern for flexibility [91]. Consequently, the techniques by which battery size can be scaled down to facilitate ease of deployment in a dispersed system as in vehicular networks have not been provided by these studies. Since achievable renewable energy varies greatly based on the geographic locations and weather conditions, the design of reliable communication systems powered by renewable energy introduces additional complexity, especially in the case of standalone off-grid systems. Wind powered off-grid BSs/RSUs is a better option in windy countries like the UK, where the solar power is limited in several geographic locations for a substantial period of the year. The previous studies by authors in [13] investigated the feasibility of a standalone wind-powered RSU in the UK and have shown that the communication QoS requirements can be met with a very small battery if a sleep mechanism is employed.

2.10 Reliability of Renewable Energy Based Networks

One major shortcoming inherent in renewable energy is its heavy dependence on stochastic atmospheric condition which invariably affects the amount of energy obtainable at any given time from the renewable energy sources. The design of reliable communication systems powered by renewable energy therefore introduces additional complexity, especially in the case of standalone off-grid systems. The stringent QoS requirement of safety applications of vehicular communication systems demands that the reliability of such system must be ensured. The reliability of an off-grid RSU powered by SSWECS is determined by the availability of sufficient wind energy. The previous studies by authors in [13] investigating the feasibility of a standalone wind-powered RSU in the UK have shown that the communication QoS requirements can be met with a very small battery if a sleep mechanism is employed. However, their study did not encompass reliability aspects. Hence, it is necessary to undertake the reliability analysis and modelling of such an RSU in the context of unavailability of sufficient wind energy. Subsequently, a number of analytic models need to be developed.

Various performance evaluation metrics, applicable to wind power systems have been defined in [92], [93] and [94]. Loss of load probability (LOLP), loss of load expectation (LOLE) and the effective load carrying capability (ELCC) are defined in [93] with regards to only wind farms that generate huge amounts of energy in the hundreds of MW range to supply large scale consumers. The concept of capacity value is defined in [93] as a means of quantifying the contribution of generating units or technologies to secure demand. The authors in [93] described the approximate methodologies for determining capacity values of power systems and also proposed a computational method for a system with non-renewable power sources integrated with wind power. The necessity of appending storage systems to the generated wind energy has also been affirmed by these papers, but with the emphasis limited to large amounts of energy without concern for flexibility. The authors in [95] have also derived indices such as LOLE, expected energy not served (EENS) and energy index of reliability (EIR) to evaluate the probabilistic reliability of off-grid hybrid solar PV-wind power system for the rural electrification in Nepal. This is also concerned with large amount of energy that is uneconomical for deployment in vehicular networks environments. Other reliability indices which can also be used to assess network performance in terms of availability and failure rate based on power supply include mean time to failure (MTTF), mean time to repair (MTTR) and mean time before failures (MTBF) [96], [97], [98]. These reliability indices have been used to define the availability of networks in terms of a forced outage rate (FOR) [98].

Some research efforts have been directed towards providing suitable energy storage for wind power systems due to their erratic nature in order to improve reliability [91], [99], [100]. There is currently a growing interest in the reliability study of power systems especially for critical telecommunication systems [101] but more importantly for determining adequacy of wind power [93]. The modelling and analysis of harnessed wind energy from the intermittent wind speed for communication systems are found to differ largely from the conventional power systems [93]. Furthermore, the authors in [94] present the reliability and economic evaluation of small autonomous power systems (SAPS) containing only renewable energy sources. The authors derived some basic probabilistic indices that define the performance of renewable energy powered systems since the conventional power systems reliability indices that are based on deterministic criteria cannot be applied in a system that contains only renewable energy sources (RES). RES have a time varying capacity which depends on the local atmospheric conditions and therefore cannot be modelled as deterministic. In order to ensure that an off-grid RSU powered by a small standalone wind energy conversion system (SSWECS) [90] is able to meet the QoS for communication traffic, the reliability of the RSU, which depends on the availability of wind and communication energy demand, must be assessed. The stochastic nature of wind power is the prime reason for the evaluation of reliability indices. The reliability modelling and analysis of an off-grid wind powered RSU, where reliability indices have been redefined in the context of variable wind power and transient energy demand, will be performed in Chapter 4. Moreover, generic methods of scaling down battery sizes to enhance the flexibility of deploying dispersed roadside vehicular systems will also be developed.

2.11 Summary

This chapter provided an overview of vehicular communication networks, their applications, architectures, environments, and standards. Previous studies related to MAC protocols, energy efficiency, renewable energy deployment and reliabilities in vehicular networks have been reviewed with the aspects needing further investigation, which constitute the motivations for the current research. A brief overview of a vehicular mobility simulator and analytical modelling of vehicular networks based on queuing theory was also given.

3 Analysis of Wind Energy and Motorway Vehicular Traffic

3.1 Introduction

Designing a resilient vehicular communication network requires a good knowledge of the dynamic traffic profile and realising a reliable model for it. The feasibility and sustainability of such a network, considering its dispersed nature, also necessitates provisioning of reliable continuous power supply to the infrastructural devices such as RSUs and BSs. Hence this chapter focusses on collation and analysis of motorway vehicular traffic and wind data with the aim of determining the energy demand of vehicular networks as well as the energy supply obtainable from wind (as this research work is primarily concerned with motorway vehicular networks with renewable energy). This is fundamental to ascertaining the feasibility of deploying wind energy sources for RSUs used in a motorway vehicular communication environment. The wind and vehicular traffic data which were obtained from the same geographical region (Reading and M4 motorway) in the UK are used for the analysis. Small size standalone wind energy systems which have benefits of low cost, easy and large scale deployments are implemented for the low power RSUs.

A detailed wind data analysis was carried out based on the hourly wind speed obtained from the UK air information resource (AIR) database [102] for a period of five years, in order to determine the energy model of deployed micro turbines used to power the RSU. Real vehicular traffic traces recorded by inductive loops on the motorway (M4 in the UK) have also been used to determine the essential traffic parameters such as flow, speed, density and inter-arrival time, which have been largely utilised in the vehicular network simulator and model designs.

3.2 Wind Energy Analysis

In order to develop a model for the harnessed wind energy from a micro-turbine, a detailed analysis of wind energy has been carried out using the hourly average wind speed samples at the RSU site which were obtained from the UK air information resource (AIR) database [102] for a period of five years. The samples were used to obtain the hourly probability distribution of wind speed which was found to follow a Weibull distribution. Several authors have concluded that the Weibull distribution is an acceptable instantaneous wind speed model [103], [104], [105]. The Weibull probability density function (pdf) is given as

$$f_v(v) = \frac{\beta}{\alpha}\left(\frac{v}{\alpha}\right)^{\beta-1} e^{-\left(\frac{v}{\alpha}\right)^{\beta}} \qquad v \geq 0 \tag{3.1}$$

where v is the instantaneous wind speed in m/s, α is the scale parameter in m/s, β is the unit-less shape parameter. The micro turbine parameters are shown in Table 3.1.

The mean and variance of Weibull distributed wind speed can be expressed as [106]

$$v_{mean} = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \tag{3.2}$$

and

$$v_{var} = \alpha^2\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \left[\Gamma\left(1 + \frac{1}{\beta}\right)\right]^2\right] \tag{3.3}$$

where $\Gamma(x)$ denotes Gamma function of x which is an extension of factorial function, with its argument shifted down by 1, i.e., $\Gamma(x) = (x-1)!$. The mean and variance of wind speed at each hour can be determined from the obtained wind data of 5 years. With the mean and variance of wind speed, the Weibull parameters α and β are computed for each hour using (3.2) and (3.3). Table 3.2 shows the hourly wind speed parameters which are needed to be able to generate actual wind speed data at each hour of the day throughout the thesis. Figure 3.1 shows the wind speed pdf and its Weibull fit.

Parameters	**Values**
Micro turbine propeller length (diameter D)	1 m [107]
Swept area (A)	0.8 m^2
Coefficient of performance (C_p)	0.45 [107]
Air density (ρ) at 15℃	1.225 kg/m^3 [102]
Cut-in speed (v_{cut-in})	3.5 m/s [108]
Cut-out speed ($v_{cut-off}$)	21 m/s [108]

Table 3-1: Micro turbine parameters.

Hour	Calculated Scale α (m/s)	Calculated Shape β	Average wind speed $\bar{v}$ (m/s) [102]
0	5.7	2.0	5.1
1	5.6	1.9	5.0
2	5.7	1.9	5.0
3	5.7	1.9	5.0
4	5.7	1.9	5.0
5	5.6	1.8	5.0
6	5.6	1.8	5.0
7	5.7	1.9	5.0
8	5.8	1.9	5.2
9	6.0	1.9	5.3
10	6.2	2.0	5.5
11	6.4	2.1	5.7
12	6.2	2.0	5.8
13	6.6	2.2	5.9
14	6.6	2.2	5.9
15	6.6	2.3	5.8
16	6.5	2.3	5.8
17	6.4	2.3	5.7
18	6.4	2.3	5.7
19	6.3	2.2	5.6
20	6.2	2.2	5.6
21	6.2	2.2	5.5
22	6.1	2.1	5.4
23	6.0	2.0	5.3

Table 3-2: Weibull parameters of instantaneous wind speed.

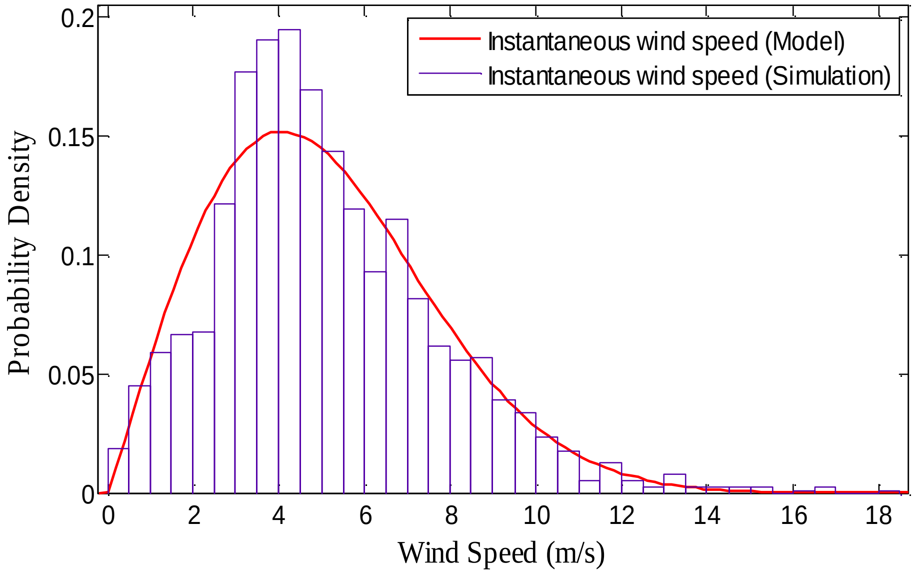

Figure 3.1: Model validation of instantaneous wind speed.

The instantaneous power harnessed from the wind can be expressed as [109]

$$P_w = \frac{1}{2} C_p \rho A v^3 \tag{3.4}$$

where ρ is the air density (in kg/m^3); A is the turbine cross-sectional-area (in m^2), v is the wind speed normal to A (in m/s); and C_p is the coefficient of performance of the wind turbine, which accounts for the decrease in the actual power harnessed from the wind due to several factors such as rotor and blade design that lead to friction and equipment losses.

Since the wind power is proportional to the third power of the wind speed as given in (3.4), the pdf of instantaneous power (P_w) which also follows a Weibull distribution [110] is given as

$$f_P(x) = \frac{\beta}{3c_t\alpha^3}\left(\frac{x}{c_t\alpha^3}\right)^{(\beta/3)-1} e^{-\left(\frac{x}{c_t\alpha^3}\right)^{\beta/3}} \qquad x \geq 0 \tag{3.5}$$

where $c_t = A\rho C_p/2$, α and β are the wind speed scale and shape parameters respectively. By comparing (3.5) with (3.1), the wind power pdf can be re-expressed in terms of wind power scale and shape parameters (α' and β') as

$$f_P(x) = \frac{\beta'}{\alpha'}\left(\frac{x}{\alpha'}\right)^{\beta'-1} e^{-\left(\frac{x}{\alpha'}\right)^{\beta'}} \qquad x \geq 0 \tag{3.6}$$

where $\alpha' = \frac{1}{2}A\rho C_p\alpha^3$; $\beta' = \frac{\beta}{3}$.

The mean and variance of Weibull distributed power can also be expressed in terms of α' and β'as [106]

$$P_{w_{mean}} = \alpha'\Gamma\left(1 + \frac{1}{\beta'}\right) \tag{3.7}$$

and

$$P_{w_{var}} = \alpha'^2\left[\Gamma\left(1 + \frac{2}{\beta'}\right) - \left[\Gamma\left(1 + \frac{1}{\beta'}\right)\right]^2\right] \tag{3.8}$$

Figure 3.2 shows both the simulated and modelled wind power while the average hourly wind energy is shown in Figure 3.3. It is evident from Figure 3.3 that the hourly average wind power is peak at hours 13.00 and 14.00 due to the prevalent high wind speed at such times.

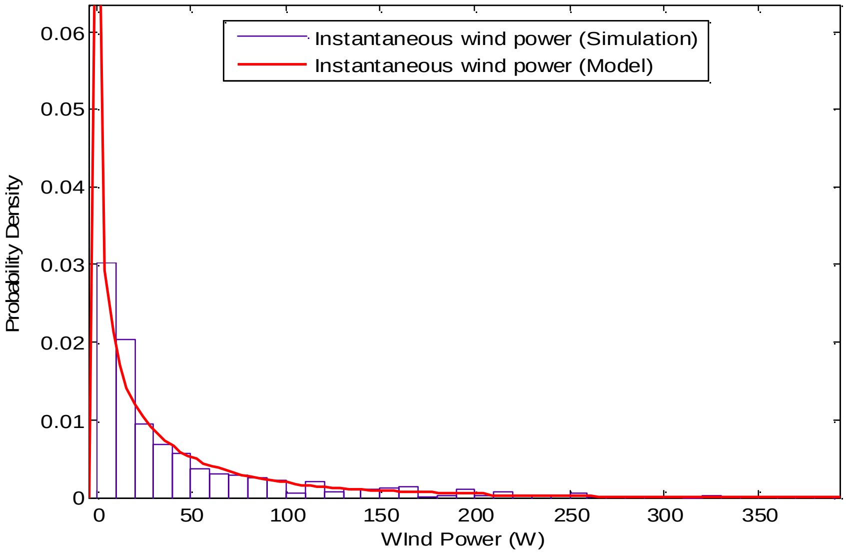

Figure 3.2: Model validation of instantaneous wind power.

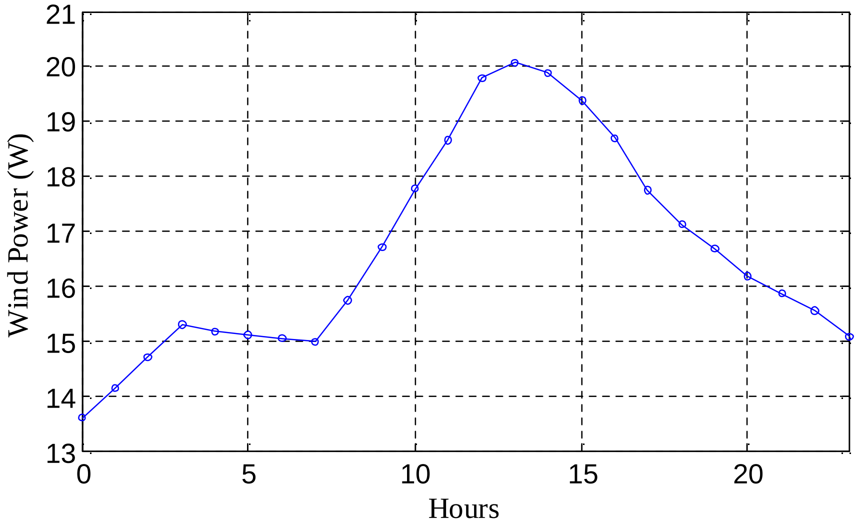

Figure 3.3: Hourly average wind energy.

3.3 Motorway vehicular traffic analysis

Evolving a robust and realistic vehicular network requires a comprehensive analysis of real vehicular traffic data to be able to develop models that truly characterise the essential parameters of vehicular mobility. The difficulty associated with modelling of vehicular mobility is premised on the complexity of factors, parameters and scenarios that impact it. These include the number of vehicles, types of vehicles, average speeds of vehicles, road network and conditions. The road network scenarios and emerging incidents affect the free flow and congestion of traffic which often translate to changing of lane, acceleration/deceleration, or absolute momentary halt. In order to realise a realistic vehicular communication system that caters for these sudden mobility changes, it is necessary to develop a mobility model that incorporates real vehicular environments with the attendant erratic features.

3.3.1 Vehicular Traffic Parameters

A detailed analysis of vehicular traffic flow data of M4 motorway in UK has been carried out to gain insight to the vital mobility characteristics that can be used to develop a realistic vehicular traffic model. The used traffic flow data were recorded by inductive loop ID 2255 on Friday April 19, 2002 from 00:00 to 23:59 hours [13]. The analysis of similar data obtained from other inductive loops at different dates and times show similar trends as ID 2255 data. Reliable and valid vehicular traffic model can be developed from the mobility characteristics based on the observed trends. The data recorded by inductive loops include lane numbers, vehicle types, traffic flow rate and average speed. The probability density function (pdf) of vehicles' inter-arrival times shown in Figure 3.4 has been obtained from the real traffic data analysis carried out. Figure 3.4 shows that the negative exponentially distributed inter-arrival times of vehicles lie mainly between 1 and 4 seconds considering the three lanes of the motorway together.

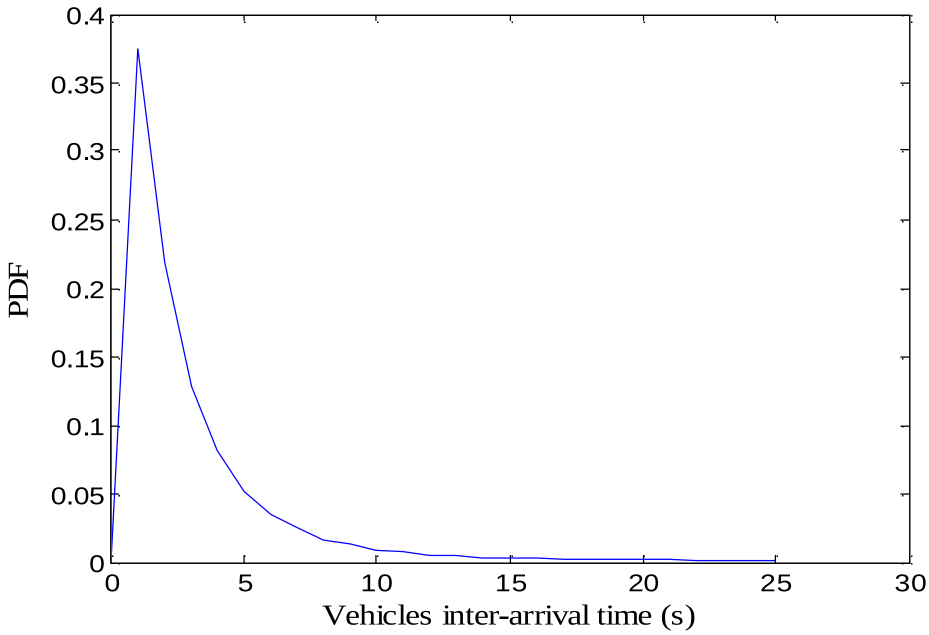

Figure 3.4: Inter-arrival time pdf of vehicles.

Figure 3.5 shows the traffic intensity per lane which is another vital traffic parameter which denotes the vehicular flow as the number of vehicles per hour in each motorway lane. The 1st lane (lane 1 - slow lane) is observed to be having the highest traffic flow in the early hours of the morning. This is due to the relatively higher number of heavy good vehicles (HGVs) travelling at the early hours of the morning compared to the other vehicle types. The HGVs always travel in the 1st lane and only change to other lanes when overtaking other vehicles or avoiding obstacles. The 2nd and 3rd lanes exhibit a rising traffic inflow above that of the 1st lane after hour 06:00 which continues until 09.00. This is a reflection of business traffic emergence of all vehicle types which persists until about 18.00 before beginning to gradually decline until they fall below the 1st lane traffic flow again.

The combined traffic flow of the three lanes is also shown in Figure 3.5 for each hour. The trend of the combined traffic flow denoted as "all lanes" indicates that the traffic intensity is maximum between the hours 15:00 and 18:00. Figure 3.5 also shows that the real traffic flow data are in good agreement with the modelled traffic data. The modelled traffic data is obtained by considering the arrival of vehicles at the inductive loop or base station on the M4 which follows a Poisson distribution since the inter-arrival times from the real data exhibit a negative exponential distribution as shown in Figure 3.4. The used real traffic data were recorded by inductive loop ID 2255 on Friday April 19, 2002 from 00:00 to 23:59 hours [13].

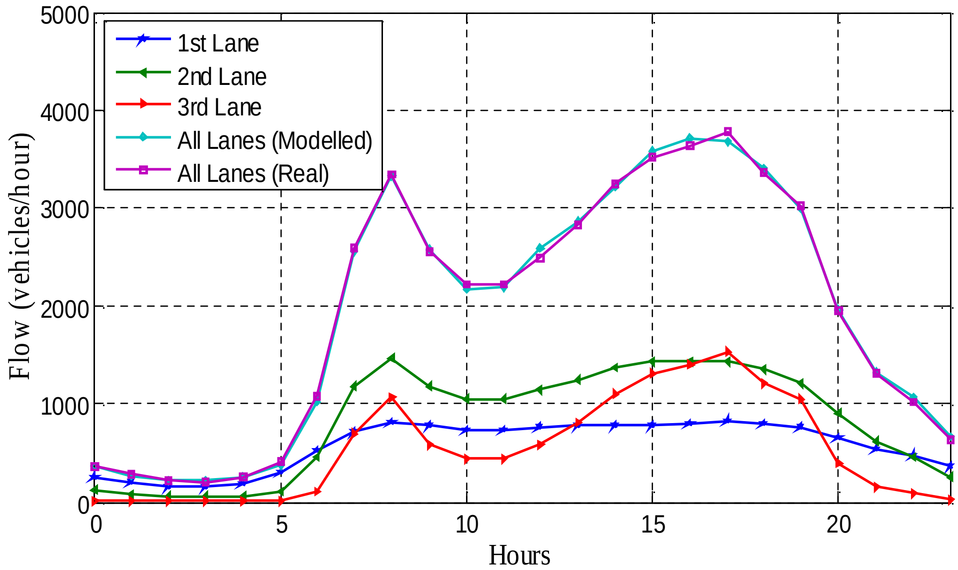

Figure 3.5: Hourly vehicular flow.

The three basic parameters used in the transportation research literature to model vehicular traffic according to vehicle traffic flow theory [111]-[112] are speed S (km/h), flow Q (vehicles/h) and density ρ_v (vehicles/km). The traffic stream model [112]-[113] approximately relates the average values of these quantities by the equation: $S = Q/\rho_v$. The vehicles are assumed to reach their free flow speed when the density approaches zero due to fewer vehicles on the motorway. Increase in the number of vehicles entering the motorway results in increased traffic density and flow until the flow reaches its maximum value. Further increase in the arriving vehicles increases the traffic density while the flow begins to decrease until the traffic density saturation point called jam density limit is reached. At the traffic jam density limit, traffic jam incident emerges, all movements stop and the traffic flow becomes zero as all vehicles are now tightly packed on the motorway. The ρ_v obtained using the traffic stream model equation is shown in Figure 3.6. The traffic flow is shown to follow the same trend as the density.

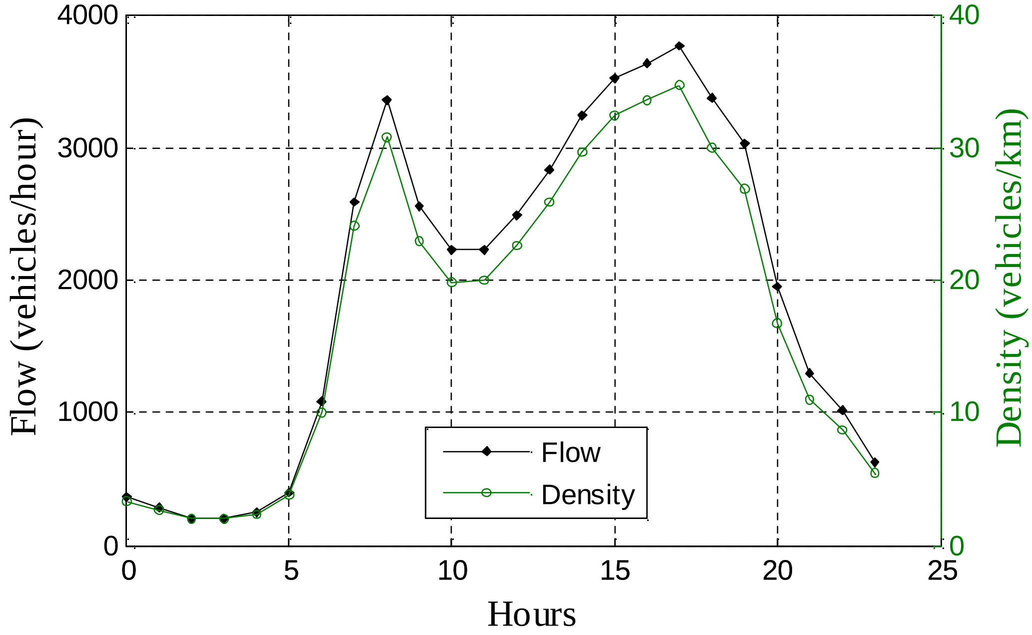

Figure 3.6: Hourly vehicular density and flow.

The average speed pdf of vehicles is shown in Figure 3.7. The pdf indicates a motorway average speed of about 30 m/s (108 km/h) which in some cases may be as low as 15 m/s and as high as 40 m/s considering traffic of all lanes and types of vehicles at all hours of the day. The used traffic flow data were recorded by inductive loop ID 2255 on Friday April 19, 2002 from 00:00 to 23:59 hours on the M4 motorway in the UK [13].

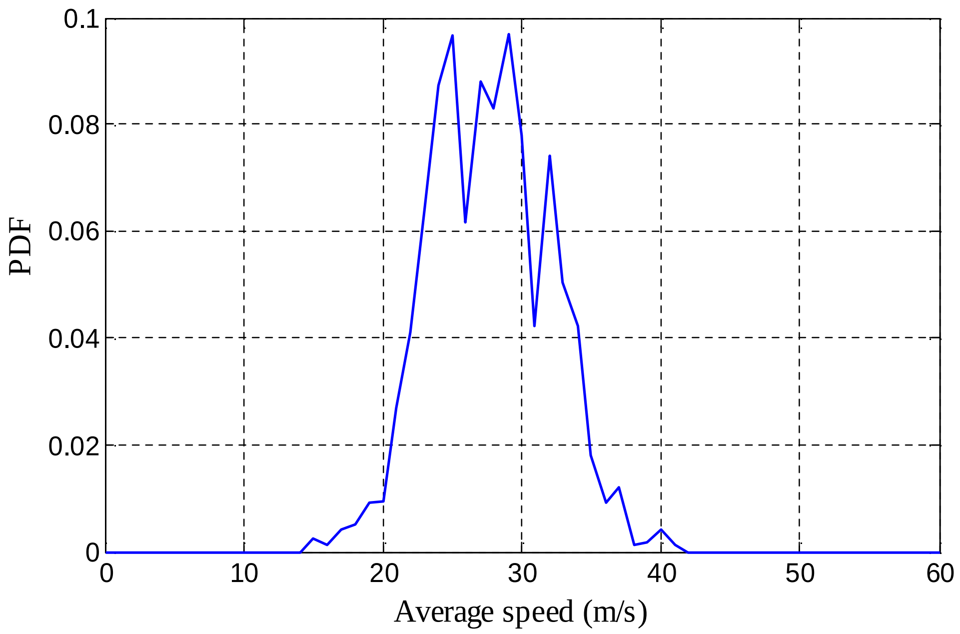

Figure 3.7: Average speed pdf of vehicles over a whole day.

The vehicles' average speed in m/s for each hour of the day is shown in Figure 3.8. The average speed is observed to fall in the early hours of the morning because HGVs travel on the motorway at this period usually move at lower average speed compared to other vehicle types. The following rise in the average speed between the hours of 07.00 and 09.00 can be attributed to the motorists driving fast to reach their offices in good time. The traffic congestion associated with afternoon rush hours which causes speed reduction accounts for the noticeable dip in the average speed at this period. The vehicle speed has been modelled by a Gaussian distribution using the parameters obtained from the traffic measurements at one minute intervals. Based on the central limit theorem, averages of random variables (such as vehicle speeds) independently drawn from independent distributions converge to a Gaussian distribution when the number of random variables is sufficiently large. Figure 3.8 shows good agreement between the modelled data and real vehicular traces. The modelled speed came from the simulator developed in the research group [36], [114] and the outputs of this simulator are used for the simulations of chapters 4 – 6 in the thesis.

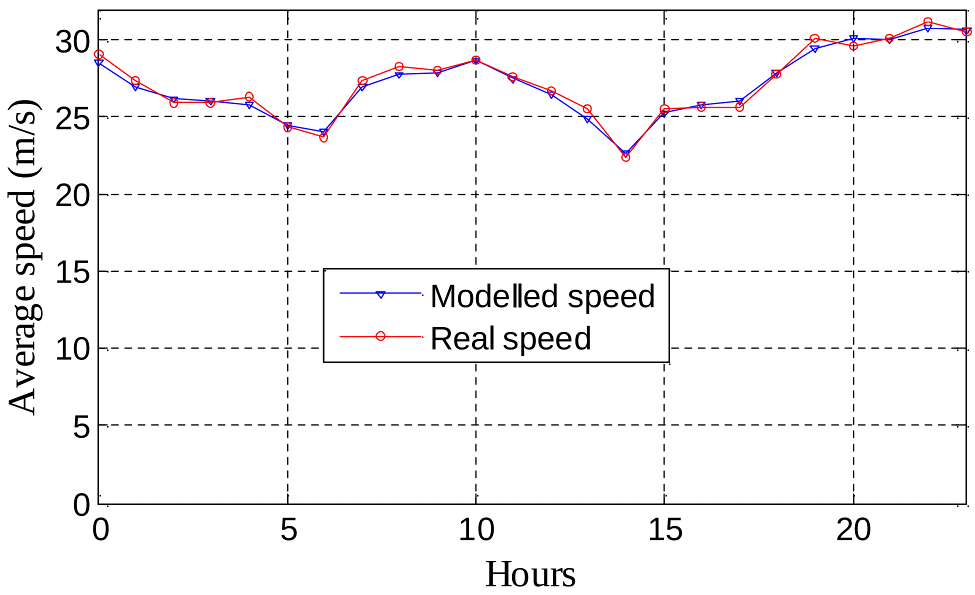

Figure 3.8: Hourly average vehicular speed.

3.4 Traffic load distribution

The traffic load distribution which represents the energy demand of the vehicular traffic can be obtained from the traffic density distribution. Since the traffic density is expressed in vehicles/km, it is reasonable to consider the traffic instantaneous load or energy demand in the context of the coverage range of motorway APs/RSUs which is a kilometer stretch. The hourly traffic in bps within a kilometer range is obtained by multiplying the traffic density by the vehicle data generation rate (d_v). The hourly traffic in bps is multiplied by

3600 to obtain the total traffic in one hour. The hourly total traffic is multiplied by energy per bit (e_b) to obtain the hourly traffic load or energy demand in Joules. Energy per bit is obtained as the ratio of AP/RSU maximum transmit power to its data rate. The hourly traffic energy demand of the studied motorway is shown in Figure 3.9. Since the hourly traffic load varies directly with the traffic density, Figures 3.9 shows a similar trend as Figure 3.6. The two peak traffic loads of 7.15 kJ and 8.05 kJ reflect the two peak traffic densities during the morning and evening rush hours of 08.00 and 17.00 respectively.

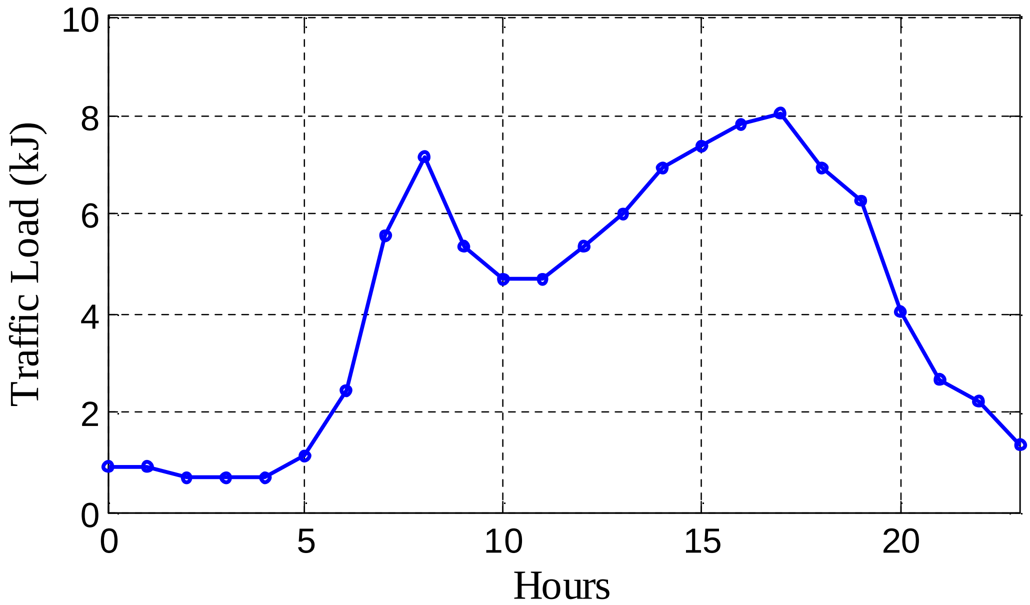

Figure 3.9: Hourly vehicular flow and density.

3.5 Summary

In this chapter, a detailed analysis of wind data obtained from the UK air information resource (AIR) database for a period of five years, has been carried out to determine the energy model of micro turbines deployable for powering the motorway RSUs. Furthermore, for the purpose of extracting vital vehicular traffic parameters such as speed, flow, density, inter-vehicle spacing and inter-arrival time to enable development of a realistic energy demand model for motorway traffic, an analysis of the M4 motorway vehicular traffic was undertaken. Real vehicular traffic traces recorded by inductive loops on the motorway (M4 in the UK) were obtained from Traffic Wales, the body responsible for Wales's traffic management in the UK.

The analyses of both wind data and vehicular traffic of the same region carried out in this chapter provided the premises for the deployment of wind energy for powering motorway RSUs in the subsequent chapters of this thesis.

4 Rate Adaptive Wind Powered RSU in a Motorway Vehicular Network

4.1 Introduction

Provisioning of ubiquitous connectivity with acceptable QoS in vehicular communication systems require that the infrastructural devices such as RSUs and BSs have uninterrupted continuous power supply. The dispersed nature of motorway vehicular networks, however, presents both economic and environmental challenges to the realisation of ubiquitous deployment requirements. While the conventional approaches that attempt to address these challenges rely on deploying energy efficient BSs with energy aware components [13], [113] and use of diesel generators for powering the dispersed network devices [11], the use of renewable energy sources such as wind or solar power [115] is however a more economical option which equally offers the advantage of mitigating the carbon foot print. In order to minimise energy consumption in vehicular communication systems, the number of high power BSs is reduced by deploying pico-cells served by low power RSUs within a macro cell that is served by the BS intermittently. This heterogeneous network offers high data rates with reduced number of BSs while satisfying the QoS criteria [14].

In this chapter, a rate adaptive technique that enhances efficient utilisation of available renewable energy is proposed for wind powered standalone (off-grid) RSUs in a motorway environment where the RSUs transmit data at various rates according to the available wind energy. Small size standalone wind energy systems which have benefits of low cost, easy and large scale deployments, are implemented for the low power RSUs. In a non-rate adaptive system, the transient nature of wind energy causes the RSUs to either transmit at full data rate or not transmit at all depending on the availability of sufficient energy. In rate adaptation, the data rate of the RSU adapts according to the available energy. Further, the RSU saves transmission energy by operating at a lower data rate, even when enough energy is available. The saved energy, in turn, is used to maintain the data rate during energy deficiency, thereby minimizing outage and improving the quality of service (QoS). An energy storage device (a small battery size) is connected to the micro wind turbine for improved service quality. Finally, the performance of the RSU with the proposed rate adaptation in terms of energy efficiency and QoS is compared with that of the non-rate adaptive RSU.

4.2 Proposed Scenario

The proposed scenario considers a single RSU from a set of RSUs typically spaced 1 km apart along a 3 lane motorway stretch, which is in line with the wireless access for the vehicular environment (WAVE) standard [116], as shown in Figure 4.1. The RSUs receive data from moving vehicles and relay the information to a base station that is beyond the transmitting range of the vehicles. The RSU is connected to a micro turbine for wind power generation through a compact re-chargeable battery. A small battery capable of supplementing the wind energy deficit is utilised to deliver an acceptable quality of service with rate adaptation. The small battery size enhances ease of deployment and maintenance of the off-grid RSUs in a motorway scenario. The performance of the proposed wind energy dependent rate adaptive RSU is investigated by focusing on one of the RSUs.

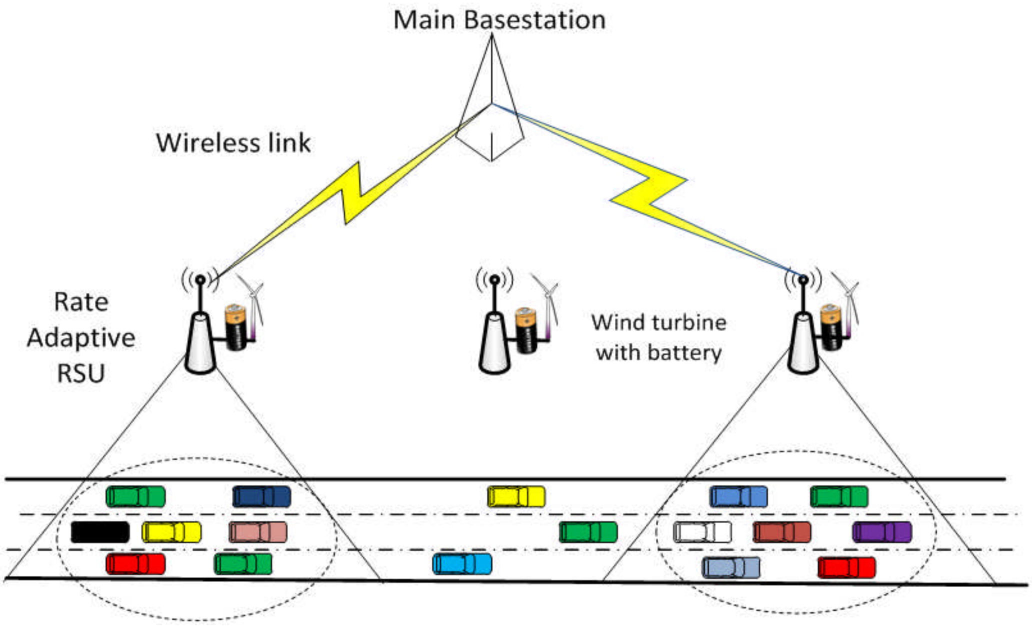

Figure 4.1: Proposed rate adaptive RSUs in a motorway.

4.3 Load Model of the RSU

The instantaneous power consumption of the RSU comprises (a) the transmission energy per unit of time which is dependent upon the varying data traffic corresponding to the vehicular density (M) and (b) the fixed power consumed by the RSU circuitry which is the minimum operational energy per unit time (P_{Idle}). Since most APs/RSUs usually have a separate transmitter circuit for ease of implementing energy efficient transmission, the receiving and listening power consumptions belong to the fixed power aspect of the devices. A typical hourly vehicular flow and densities obtained from the M4 motorway (UK) which lies within the same geographical location where the wind data were taken are used to determine the traffic load at the RSU. Detailed analysis of the available wind energy and the traffic flow of the study region have been reported in Chapter 3. The instantaneous transmission energy consumption by the RSU follows a Normal distribution with mean (μ) and variance (σ) according to the vehicular density. This is because the transmission energy consumption by the RSU equals the traffic load or energy demand (as obtained in Chapter 3) which directly depends on the product of traffic density and energy per bit. Packet arrivals are Poisson distributed, however energy per bit is evaluated over a very short time period and is approximated as a Gaussian random variable. Gaussian distribution is an excellent approximation of a Poisson distribution when the total number of events becomes sufficiently large [117].

Since the operational energy per unit time (P_{Idle}) is fixed, the probability density function of the energy consumption model can be expressed as

$$f(P_L) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{((P_L - P_{Idle}) - \mu)^2}{2\sigma^2}} \tag{4.1}$$

where the random variable P_L denotes the total energy consumption of the RSU per unit time. The parameters μ and σ represent the mean and variance of the transmission energy consumption. Figure 4.2 shows the hourly average energy consumption by the RSU, which represents the summation of traffic energy demand and the fixed operational energy consumption of the RSU at each hour.

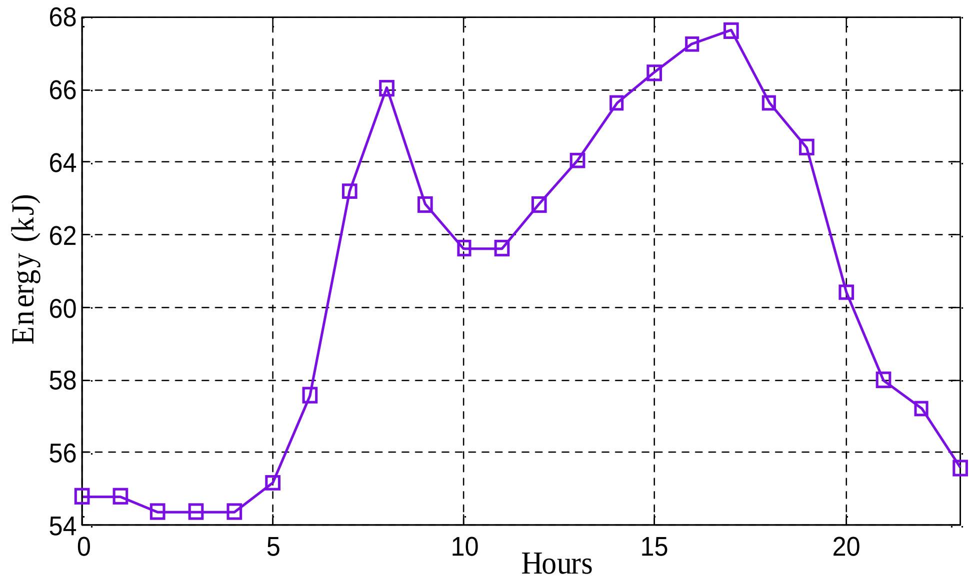

Figure 4.2: Hourly average energy consumption by an RSU.

In non-rate-adaptive system where the RSU transmits at 0 or 27 Mbps (full data rate), the total power consumption can be expressed as

$$P_{NRA}^{RSU} = P_{Idle} + P_{t-max} \quad (4.2)$$

where P_{t-max} is the maximum transmission power of the RSU. In this scenario the RSU either transmits at full data rate using the maximum transmission power or fails to transmit based on the unavailability of P_{t-max}. This results in several moments of transmission outage in situations where the energy source is purely renewable and off-grid (as in this deployment where only wind energy source is used) considering its transient nature. In rate-adaptive RSU, the total power consumption can be expressed as

$$P_{RA}^{RSU} = P_{Idle} + P_{t-var} \quad (4.3)$$

where P_{t-var} is the variable transmission power which depends on the available energy for transmission. In order to obtain a transmitting data rate for each instance of P_{t-var}, the transmitting energy per bit was obtained from the transmitter power (P_{t-max}) at the maximum data rate (27 Mb/s). Weibull power was generated, P_{Idle} was subtracted from this power, and the remaining part if above zero was used with the energy per bit value to determine the data rate. The adaptive data rate (d_{r-var}) is linearly proportional to P_{t-var} since the transmitting energy per bit (J/s) is fixed for transmitters [118]. Hence, (4.3) can be re-expressed in terms of adaptive or variable data rate as

$$P_{RA}^{RSU} = P_{Idle} + P_{t-max} \frac{d_{r-var}}{d_{r-max}} \quad (4.4)$$

The various system parameters used in this study are given in Table 4.1.

Parameter	Notation	Value
Max. operational power	P_{RSU}	20 W [119]
Min. operational power	P_{Idle}	$\frac{P_{RSU}}{1.4} = 14.8$ W [56]
Max transmit Power	P_{t-max}	$P_{RSU} - P_{Idle} = 5.2$ W
Mean Vehicle data generation rate	d_v	320 kbps
Average packet size	P_s	867.4 Bytes
RSU max data rate	d_{r-max}	27 Mbps [3]

Table 4-1: System Parameters

Figure 4.3 shows the data rate distributions for non-rate adaptation for the operating cases of (1) wind energy only and (2) wind energy with battery. It is evident from Figure 4.3 that non-rate adaptation is fraught with unacceptable RSU outages due to high percentage of zero data rates. In the case of wind energy only, there is high probability of 0 Mb/s data rate and the distribution between 0 Mb/s and 27 Mb/s is also very low due to absence of battery. The RSU transmits only at full data rate (27 Mbps) when it has sufficient transmitting power. This is also true for the case of wind energy with battery without the adaptive rate algorithm that leverages the battery energy (except that it has a lower 0 Mb/s data rate probability and higher 27 Mb/s data rate probability). This is because the data rate varies directly with transmission power which is cubic proportional to the instantaneous wind speed. Hence, a small variation in wind speed presents a huge difference in transmission power and consequently the data rate.

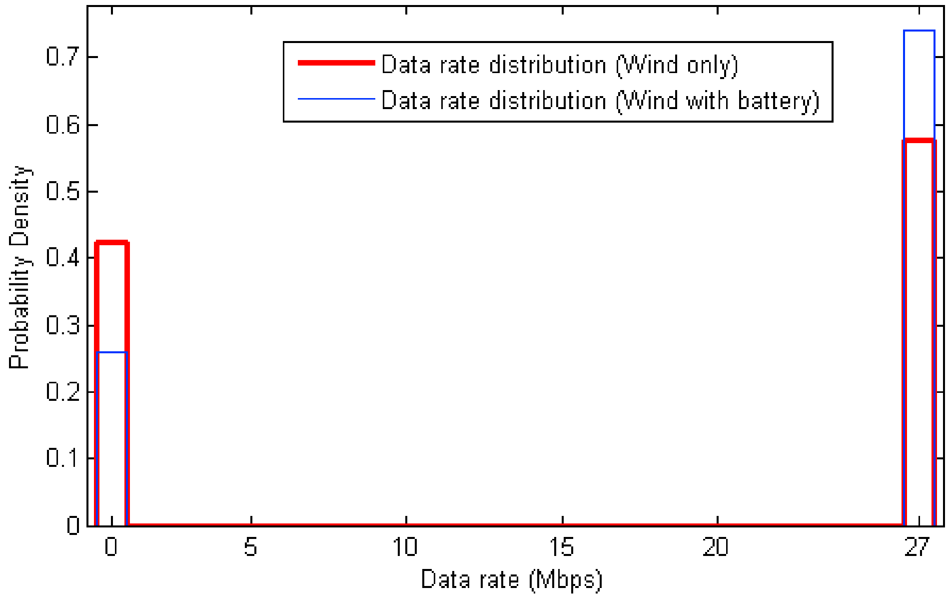

Figure 4.3: Data rate distribution for non-rate adaptive RSU.

4.4 Wind Energy Dependent Rate Adaptation

The first step for rate adaptation is to obtain the wind energy available for transmission (E_{t-var}). This is essentially the difference between instantaneous wind energy available (E_w) and the RSU operational energy consumption (E_{Idle}). A positive E_{t-var} implies that the wind energy is sufficient to enable the RSU to transmit at certain data rates depending on the magnitude of E_{t-var}. If E_{t-var} is negative, the RSU draws the transmission energy from the battery. A small battery of 22.7 Ah with 50% depth of discharge (DOD) (about half size of an automobile battery) is used in this deployment [120]. The amount of energy drawn is N% of the maximum capacity of the battery. The parameter N is Normal distributed. If E_{t-var} is positive and greater than the maximum transmission energy (E_{t-max}), then the surplus plus S% of E_{t-max} is used to charge the battery. The parameter S is also a Normal distributed variable. The parameters N and S in the designed adaptive rate algorithm are Normal distributed for the reason that the transmission energy (RSU load) is Gaussian distributed as explained earlier. Since the load demand is Gaussian distributed, the battery charge and discharge levels are Gaussian distributed and hence N and S are Gaussian distributed.

The corresponding algorithm (Algorithm 1) results in a new transmission energy distribution (E_{t-var}) that determines the RSU data rate (d_{r_var}). The adaptive rate algorithm works by computing the transmission energy (E_t) that is obtainable from the generated wind energy (E_w) at each instance of the wind energy sample generated. If E_t is greater than zero and less than the maximum transmission energy (E_{t-max}), a data rate is computed based on E_t. When E_t is greater than E_{t-max}, the surplus plus S% of E_{t-max} is used to charge the battery while the data rate is computed based on the remaining energy. The RSU draws energy (N% of the maximum capacity of the battery) from the battery when E_t is less than zero with the corresponding data rate based on the drawn energy value.

Algorithm 1 for adaptive data rate

Input: E_w, E_{Idle} *and Load* (E_L)

Output: Data rate

for all $j \in Z$ **do** // Z=total no of samples
    input E_w *and* E_{op};
    Compute E_t;
    if $0 < E_t < E_{t-max}$ **then**
        compute data rate;
    else if $E_t < 0$ **then**
        power RSU with *N*% of the max battery capacity;
        recompute data rate;
    else if $E_t > E_{t-max}$ **then**
        charge the battery with surplus and *S*% of E_{t-max};
        recompute data rate;
    end if
end for

The mean and standard deviation of *N* used in the algorithm are 20 and 8.1 respectively, while the mean and standard deviation of S are 25 and 12.9 respectively. The choice of *N* and *S* values were based on careful analysis of energy deficit/surplus obtained from the difference of instantaneous wind energy and load demand. In order to obtain the optimal values of *N* and *S*, the performance of the rate adaptive RSU was investigated by using different values of *N* and *S* and the corresponding data rate distributions. The values of *N* and *S* that yielded the best system performance were finally selected for the proposed adaptive rate scheme. The Guassian distributed *N* and *S* improve the data rate spread of the RSU as shown in Figure 4.4 while maximising the available wind energy usage in a way that minimises outages.

The obtained pdf of the data rate is shown in Figure 4.4. The data rate distribution is 24.3% 27 Mbps, 67.3% Normal distribution with mean 19.9 Mbps and standard deviation 3.6 Mbps, and 8.4% 3.0 Mbps. The inset in Figure 4.4 shows the mainly Gaussian distributed portion which is 10 Mbps – 26.9 Mbps only. Although the obtained data rate distribution by this algorithm is based on the hourly wind and traffic data, the scheme can readily yield a data rate distribution with higher time resolution of say, 30 minutes or less, without much modification. The moment the distribution parameters of the inputs (wind and traffic data) at the desired time scale (resolution) are obtained, the proposed algorithm can be applied to obtain the corresponding data rate distribution.

Due to the presence of the battery coupled with the rate adaptation scheme, the Gaussian distribution in Figure 4.4 (which is enlarged for better view in the inset) has larger mean compared to the case of non-rate adaptation shown in Figure 4.3, hence enhancing the service quality of the RSU.

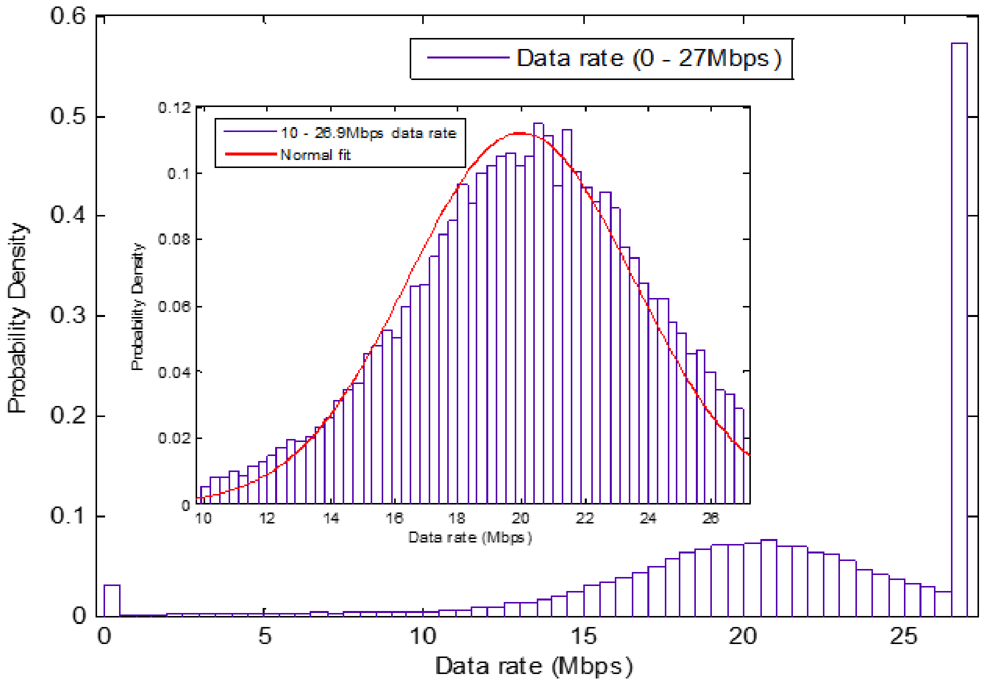

Figure 4.4: Adaptive rate distribution (0 – 27 Mbps).

The proposed wind power-based rate adaptive technique reduces the system outages by providing improved spread of data rates as against the mainly 0 and 27 Mbps data rates of non-rate adaptation scheme in figure 4.3. High packet loss occurs when the RSU is designed to transmit only at 0 and 27 Mbps. If large energy is drawn from the battery to always operate at 27 Mbps, then this will need a large battery and will lead to energy wastage as all demands are not always at maximum rate of 27 Mbps. It is better therefore to have a range of possible data rates. Not knowing the requested data rate statistics, a Gaussian spread of data rates was adopted through N and S percentages used in the algorithm. It should be noted that spread of data rates is application specific. With the proposed rate adaptive algorithm, the RSU has a service outage of only 1% (which represents 99% service availability) while in the two cases of non-rate adaptation, the service outages are 34%

and 8% for the wind energy only and wind energy with battery respectively. The service outage and availability for the various cases considered were obtained from the pairwise comparison of load demand and the available power supply (wind power with and without battery). Service outage occurs when the load demand exceeds the available power supply for the non-rate adaptive cases.

4.5 Analytical Modelling of Rate Adaptive RSU Performance

The proposed rate adaptive RSU can be modelled by M/G/1/K/M queue where M represents the Poisson arrival of packets from the vehicles, G refers to the General distributed service time by the RSU and K represents the buffer size which denotes the maximum capacity of the RSU. Since the queue is of finite capacity, packets that arrive when the buffer is full are blocked or lost. The blocking probability (P_b) which is the probability of packets being lost as a result of a full buffer, as well as delay are therefore crucial performance metrics for a finite capacity system. The queueing model can be solved using an embedded Markov chain. The Poisson distributed packet arrivals from M vehicles has mean arrival rate λ' while the General distributed service times has mean service time $\bar{x} = \mu^{-1}$ and probability density function $b(t)$. The QoS metrics of the RSU can therefore be computed based on the equilibrium state probability p_k obtained for $M/G/1/K$queue in [121]. The mean queue length which denotes the total number of packets in the system is expressed as

$$N = \sum_{k=0}^{K} k\, p_k \tag{4.5}$$

The packet blocking probability (P_b) which is the probability of arriving packets meeting a full RSU is expressed as

$$P_b = p_K \tag{4.6}$$

The system utilisation is given as

$$U = M\lambda' \bar{x}(1 - P_b) \tag{4.7}$$

where $\bar{x} = \mu^{-1}$ is the mean service time.

The mean total time spent in the system by a packet according to Little's law [122] becomes

$$W = \frac{N}{M\lambda'(1-P_b)} \tag{4.8}$$

The transmission energy, E_t, expended per hour can be expressed as

$$E_t = U \times P_t \times 3600 \tag{4.9}$$

where P_t is the average transmitting power.

4.6 Performance Evaluation

The performance of the rate adaptive wind powered RSU has been investigated in terms of average packet delay, packet blocking probability, utilisation and energy consumption. A JAVA based event-driven simulation based on the real vehicular traffic measurements from the M4 motorway, UK, has been used to validate the analytical model. The merit of the wind energy based rate adaptive strategy implemented in the standalone RSU is investigated by comparing its performance with non-rate adaptive operation in terms of transmission energy consumed, average packet delay and packet blocking probability.

Figure 4.5 shows the average packet delay of the rate adaptive system with varying vehicular load according to the hours of the day and buffer size. As expected the average packet delay increases with increase in buffer size as more number of packets admitted into the buffer queue have to wait for a longer period of time to be served. The average packet delays for the different buffer sizes investigated show a similar trend in respect to the vehicular load with peak values at hours 8.00 and 17.00 which are two daily rush hours of resuming and returning from work. The buffer size of 20 proves to be optimal as further increases to 30, 40 and 50 show no change in the average packet delay. This is also true for utilisation and packet blocking probability shown in Figure 4.6 and Figure 4.7 respectively. The average packet delays which range between 0.4 ms and 1.2 ms in all studied cases of wind energy based rate adaptive RSU are within the acceptable range of quality multimedia services. The average packet delay in Figure 4.5 is fairly constant for the first five hours of the day as these hours have fairly equal average vehicular densities and traffic loads as shown in Figure 3.6 and Figure 3.9 of Chapter 3 based on the collated traffic data.

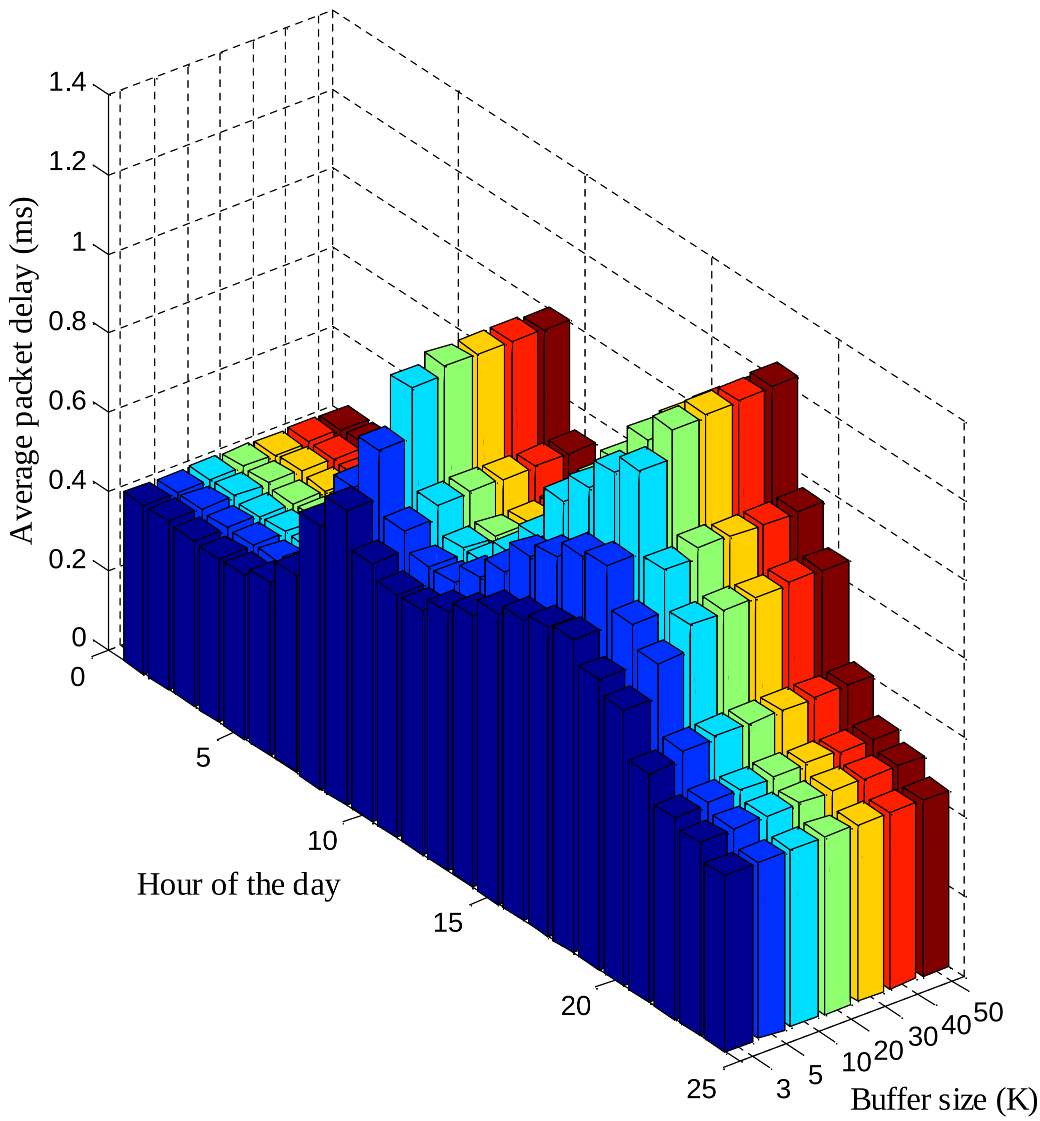

Figure 4.5: Average packet delay with varying buffer size and hour of the day for rate adaptive RSU.

The performance of rate adaptive RSU in terms of packet blocking probability with respect to varying buffer size and hourly traffic load is shown in Figure 4.6. While larger buffer sizes degrade average packet delays as observed in Figure 4.5, they however improve the packet blocking probability as more packets that would have been dropped due to buffer overflow are accommodated in larger buffers to be served at later times. While the packet blocking probabilities are mainly zero with the highest value being 0.006 with buffer sizes of 10 and above, they attain high and unacceptable values of 0.04 and 0.08 with buffer sizes of 5 and 3 respectively during peak traffic hours.

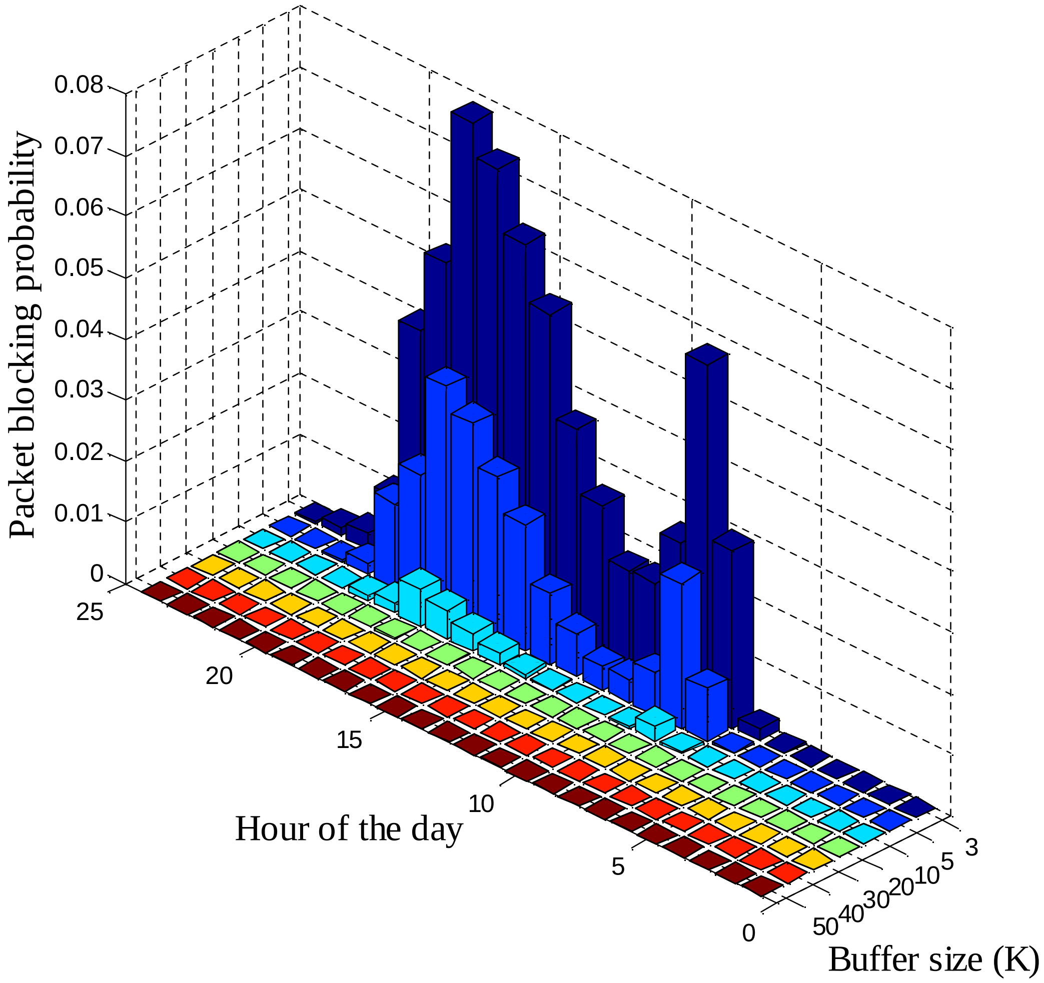

Figure 4.6: Packet blocking probability with varying buffer size and hour of the day for rate adaptive RSU.

Figure 4.7 shows the utilisation of the rate adaptive system with varying hourly vehicular load and buffer size. The utilisation which basically depends on the carried load and system capacity follows the hourly vehicular density trend with dual peak values at hours 8.00 and 17.00 as discussed in Chapter 3. The rate adaptive system with smaller buffer sizes have marginally lower utilisations due to their low carried loads as a result of packet blockages. Increase in buffer size beyond the optimal level that offers minimal blockage (i.e. buffer size of 20) introduces no noticeable change to the utilisation.

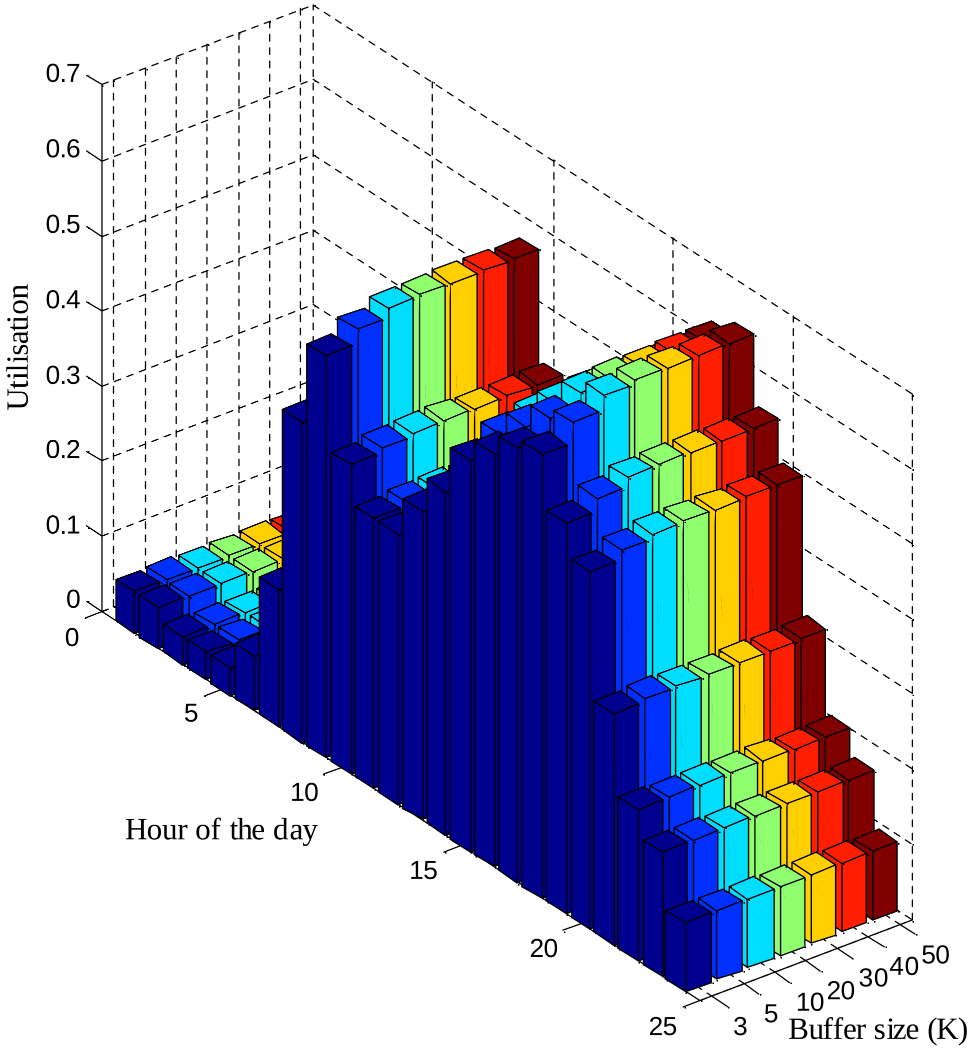

Figure 4.7: Utilisation with varying buffer size and hour of the day for rate adaptive RSU.

Figure 4.8 shows the variation of average packet delay of a non-rate adaptive RSU with hourly vehicular load and varying buffer size. In this scenario, the non-rate adaptive RSU has sufficient power supply (grid connection) which enables transmission at full data rate (27 Mbps) at all times. While the average packet delay increases with increase in buffer size and vehicular density as in the rate adaptive case, the average packet delays which range between 0.3

ms and 0.4 ms are however much lower. This is due to the lower waiting time of the packets in the buffer as they are constantly served at full data rate. This is at the expense of transmission energy which the proposed rate adaptive technique aims to minimise in the wind energy based standalone RSU deployment. The average packet delay in Figure 4.8 is fairly constant for the first five hours of the day as these hours have fairly equal average vehicular densities and traffic loads as shown in Figure 3.6 and Figure 3.9 of Chapter 3 based on the collated traffic data.

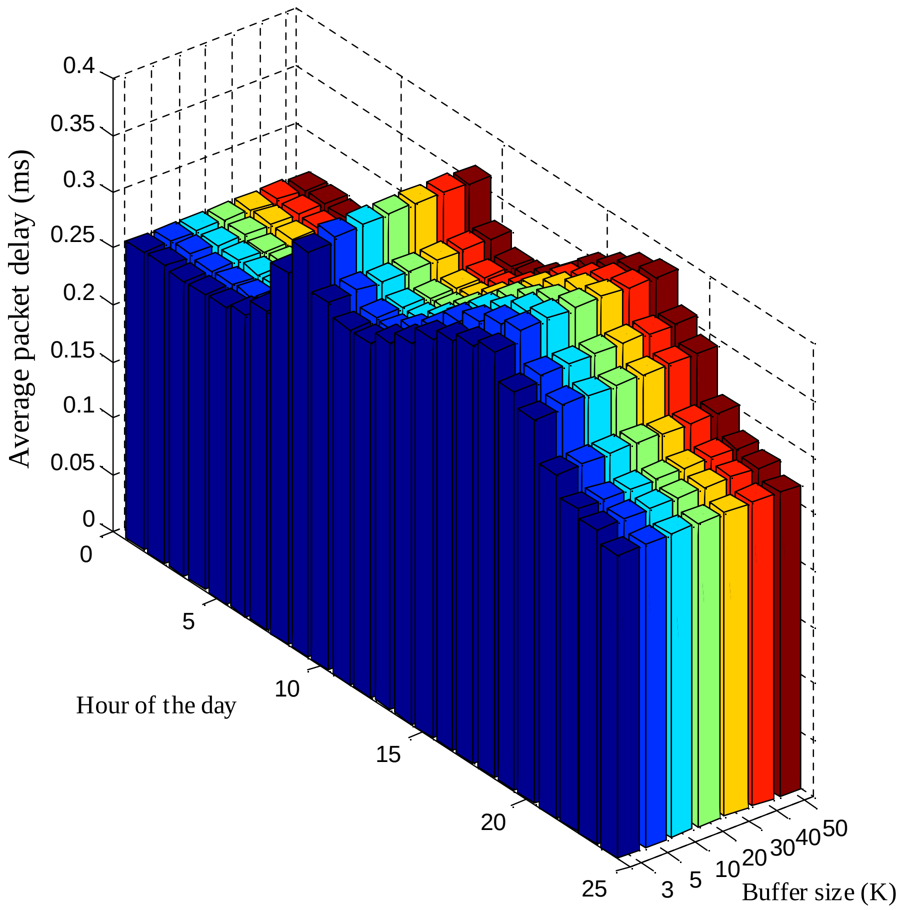

Figure 4.8: Average packet delay with varying buffer size and hour of the day for non-rate adaptive RSU.

The packet blocking probability (PBP) of non-rate adaptive RSU with respect to varying buffer size and hourly traffic load is shown in Figure 4.9. While larger buffer sizes degrade the average packet delays as observed in Figure 4.8, they improve the packet blocking probability as more packets that would have be dropped due to buffer overflow are received in the larger buffers to be served at later times. For the same reason with full transmission rate and faster service as in Figure 4.8, the PBPs of a non-rate adaptive RSU which are mainly zero, with a maximum of 0.008, are lower than that of rate adaptive RSU.

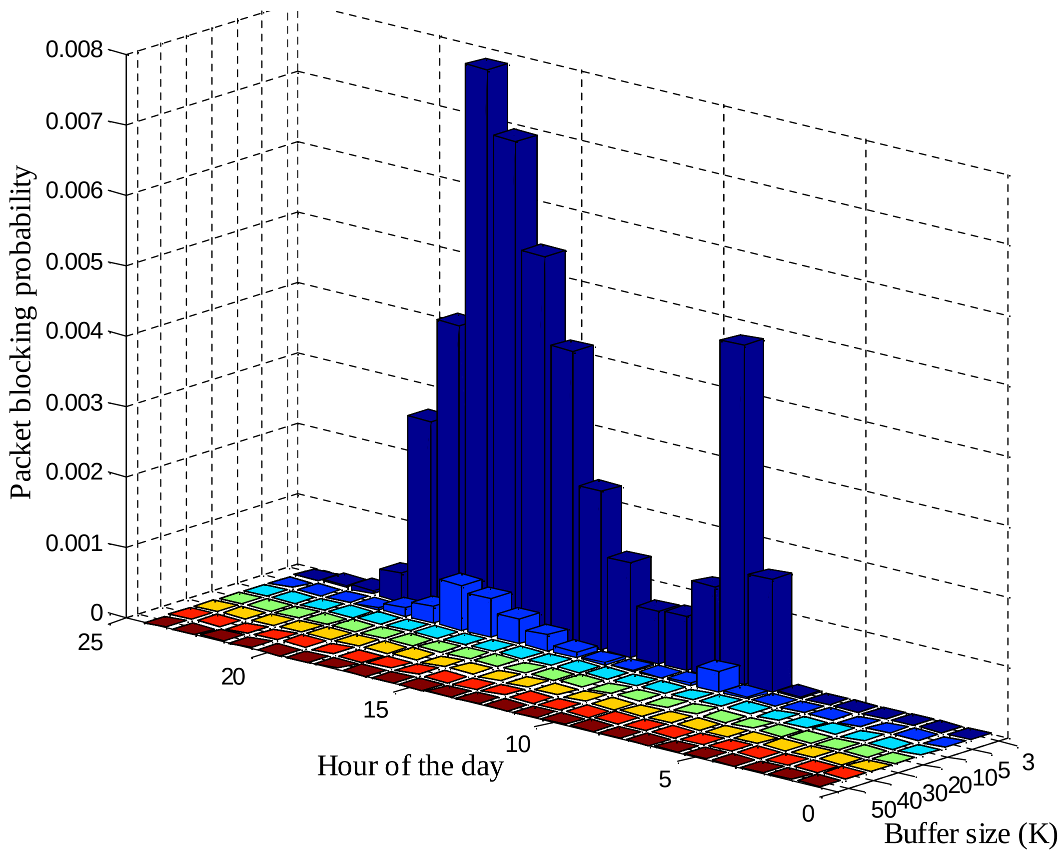

Figure 4.9: Packet blocking probability with varying buffer size and hour of the day for non-rate adaptive RSU.

Figure 4.10 shows the utilisation of the non-rate adaptive system with varying hourly vehicular load and buffer size. The utilisation follows the hourly vehicular density trend with dual peak values at hours 8.00 and 17.00 in a similar way to the rate adaptive case except that the utilisations for the various buffer sizes are fairly equal. This is due to the relatively steady carried loads as the PBPs are mainly zero with all buffer sizes as a result of high transmission rate.

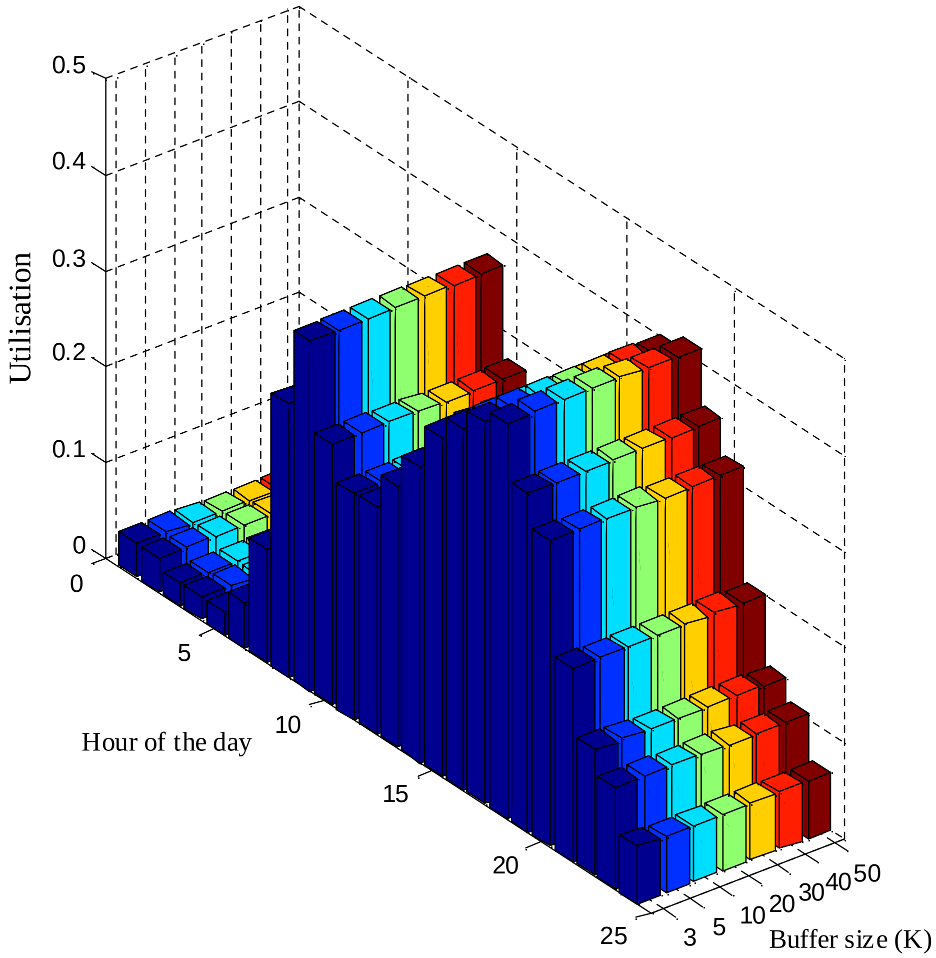

Figure 4.10: Utilisation with varying buffer size and hour of the day for non-rate adaptive RSU.

The validation of the proposed queue model (M/G/1/K) for the wind power based rate adaptive RSU by the simulation is shown in Figure 4.11 – Figure

4.12 in terms of QoS metrics such as average packet delay, packet blocking probability and utilisation.

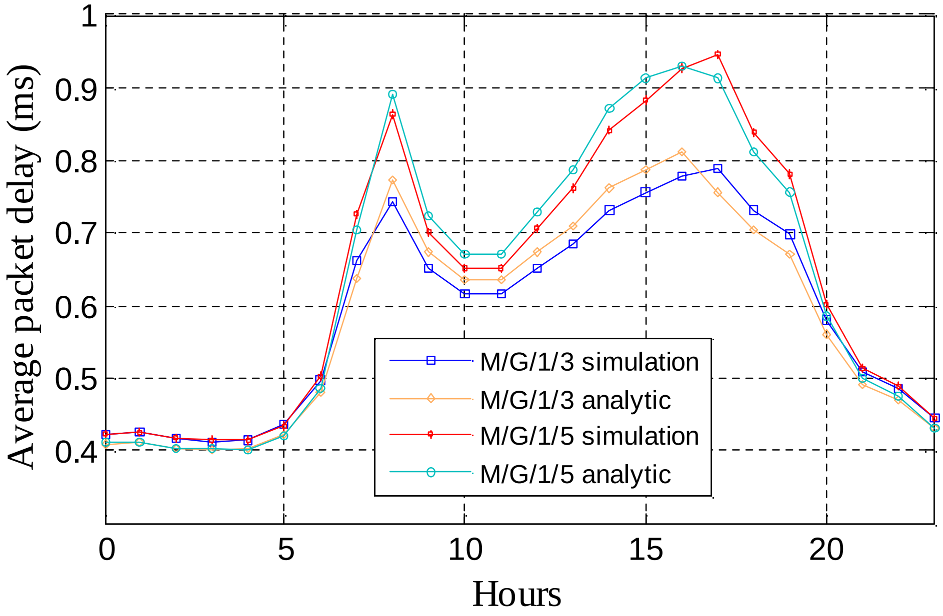

Figure 4.11: Average packet delay with hourly traffic load.

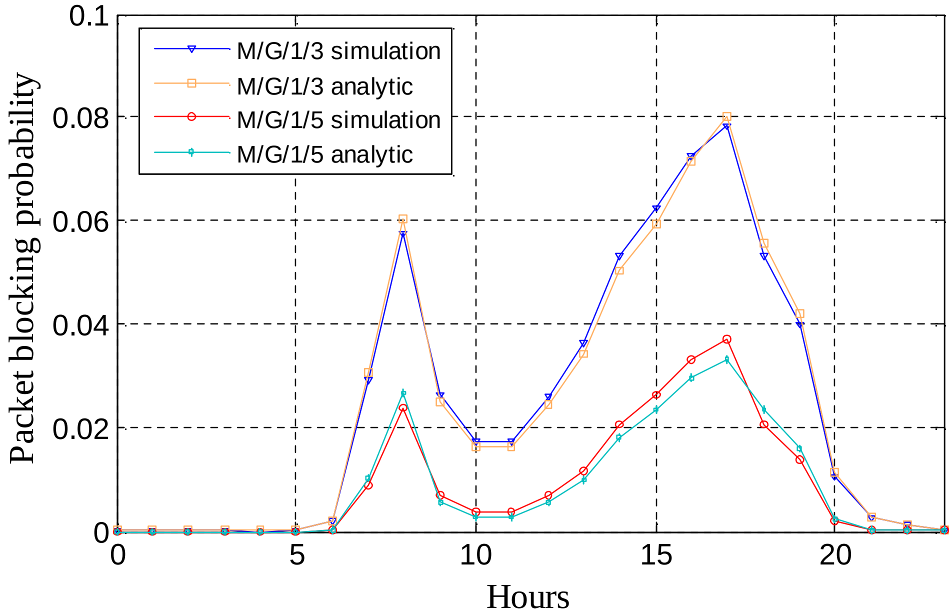

Figure 4.12: Packet blocking probability with hourly traffic load.

As explained earlier, the average packet delays for the buffer sizes of 3 and 5 in Figure 4.11 are low (between 0.4 ms and 0.9 ms) due to the low number of packets being served as a result of high packet blockage as shown in Figure 4.12. The RSU with buffer sizes of 3 and 5 have poor blocking probabilities of 8% and 3.7% respectively at peak periods. Larger buffer sizes of 10 and above (as shown earlier in Figure 4.8 – Figure 4.10) with better throughputs are therefore optimal for the proposed wind power-based rate adaptive RSU. In Figure 4.13, the RSU with buffer sizes of 3 and 5 shows fairly similar hourly utilisation that closely follows the traffic density variation pattern. The buffer size of 5 has a marginally higher utilisation during peak hours due to higher carried load at such moments.

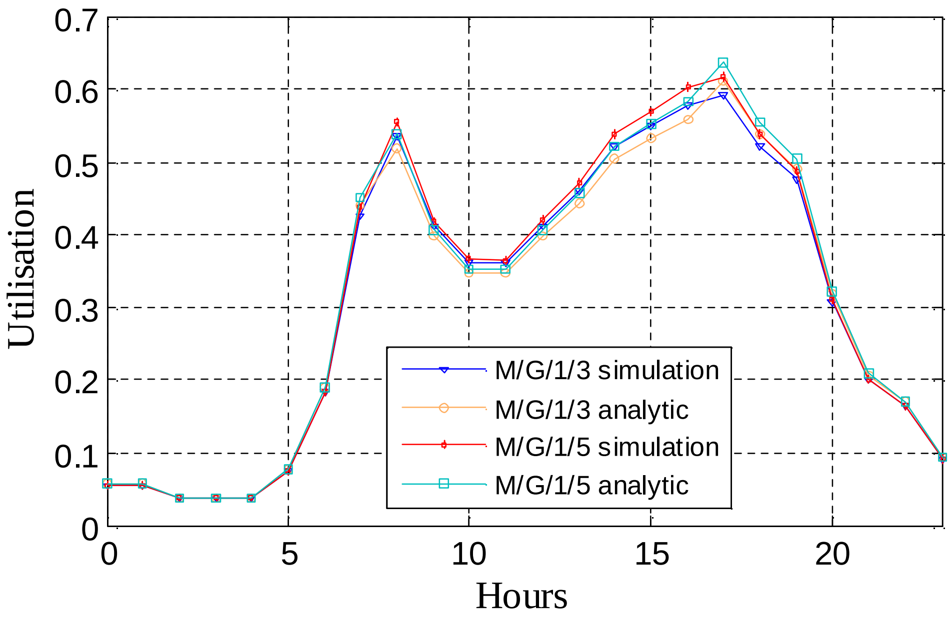

Figure 4.13: Utilisation with hourly traffic load.

The hourly transmission energy consumed by the wind powered rate adaptive RSU is compared with that of non-rate adaptive RSU in Figure 4.14. The non-rate adaptive RSU which transmits at full date rate of 27 Mbps at all times consumes transmission energy of 5.2 Wh hourly and 125.7 Wh daily. The hourly consumed transmission energy of the adaptive rate RSU ranges between 2.9 Wh and 4.8 Wh with the daily total transmission energy of 96.6 Wh. This offers a daily energy saving of 29.1 Wh which is 23% of the daily energy consumption of a non-adaptive rate system. Hence, the deployment of wind energy based rate adaptive technique in RSU is an effective energy efficiency strategy which does not degrade the service quality of the system as both the average packet delay and PBP remain within the acceptable limits (see Figure 4.8 to Figure 4.10) that guarantee high quality vehicular communication services.

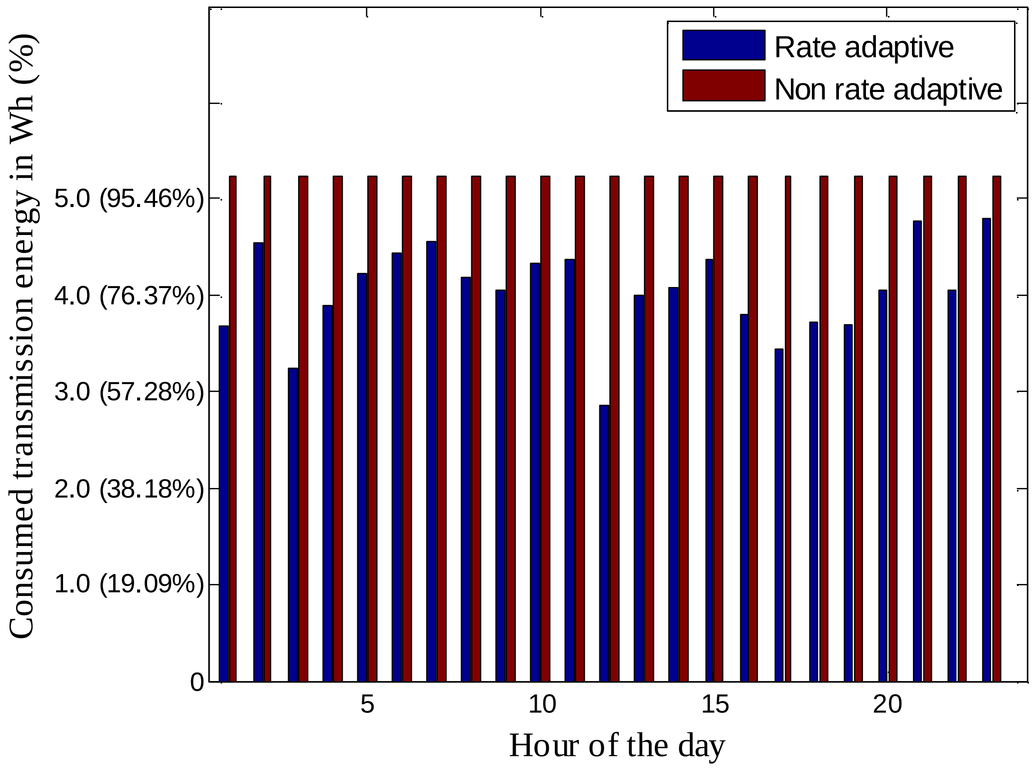

Figure 4.14: Consumed transmission energy by the RSU.

4.7 Summary

With the primary aim of deploying renewable energy resource which reduces the carbon footprint with improved energy efficiency, a rate adaptive RSU that provides coverage along a motorway stretch was proposed and evaluated in vehicular networks. In this chapter, analytic models for both wind energy and real vehicular traffic obtained in Chapter 3 were used to develop the adaptive data rate algorithm for RSUs in motorway vehicular networks. The performance of the modelled and simulated wind energy based rate adaptive RSU was investigated in terms of consumed transmission energy, average packet delay and PBP. The proposed wind power-based rate adaptive technique reduced the system outages by providing improved spread of data rates as against the mainly 0 and 27 Mbps data rates of non-rate adaptation scheme. With the rate adaptive algorithm, the RSU has a service outage of only 1% (which represents 99% service availability) while in the two cases of non-rate adaptation, the service outages are 34% and 8% for the wind energy only and wind energy with battery respectively. The proposed wind powered rate adaptive RSU offered a power margin of 23% when compared with a non-rate adaptive RSU while satisfying the required service quality.

5 Wind Powered RSU Performance with Channel Fading

5.1 Introduction

Green vehicular networks, especially infrastructure-based vehicular networks, which have the presence of central infrastructures in the form of access points (APs), RSUs or BSs, offer the dual benefits of reducing both the carbon footprint and the operation expenditure (OPEX) of the communication system. The presence of central infrastructures provides improved quality, resilience and reliability to the network. Wind powered off-grid BSs/RSUs in windy countries like the UK, where the solar power is limited in several geographic locations for a substantial period of the year, finds ready application in sparse areas like countryside and motorways that lack the supply from the national grid for economic reasons. However, the stringent performance requirements of vehicular communication systems due to the critical services they offer poses challenges to the greening initiative in an off-grid deployment.

The previous studies by authors in [13] investigated the feasibility of a standalone wind-powered RSU in the UK and have shown that the communication QoS requirements can be met with a very small battery if a sleep mechanism is employed. However, the option of maximising the energy efficiency of the RSU through rate adaptation was not explored. The authors in [123] proposed a wind energy dependent rate adaptation for RSU in vehicular networks without implementing the effects of real channel characteristics of the studied environment. A detailed investigation of the effects of fading on motorway vehicular network with wind powered rate adaptive RSU is lacking in the literature. The work in this chapter attempts to fill these gaps by understudying the performance of wind powered RSU with channel fading in terms of packet blockage probability, average packet delay and utilisation. To obtain a realistic performance evaluation, Rician fading is considered due to the typical presence of a line of sight component between vehicles and RSU. The Rician fading parameters in a motorway environment and their impact on the generated packets from the vehicles are analysed to obtain the packet throughput received at the RSU for onward transmission. The off grid RSU in the dispersed motorway environment is powered solely by an economical and easy to deploy small standalone wind energy conversion systems (SSWECS). Wind energy-based rate adaptation is deployed in the RSU to enhance the efficient utilisation of available energy (considering the intermittent nature of wind energy). In this study the real vehicular traffic profiles and wind data for a specified motorway region have been utilised.

5.2 Proposed Scenario

A centralised motorway vehicular communication system consisting of equally spaced RSUs along a three lane stretch as shown in Figure 5.1 is considered in this study. The RSUs receive data from moving vehicles within their coverage areas and relay the information to a BS that is beyond the transmitting range of the vehicles in an architecture similar to the hierarchical macro–micro cellular topology [14]. Each wind powered RSU is connected to a micro turbine through a compact chargeable battery. A small battery capable of supplementing the wind energy deficit to deliver acceptable quality of service with rate adaptation is utilised. The compact architecture of micro turbine with small battery size facilitates ease of deployment and maintenance of the off-grid RSUs in a motorway scenario. The parameters for the small standalone wind energy conversion system (SSWECS) as well as the system communication parameters are shown in Table 5.1.

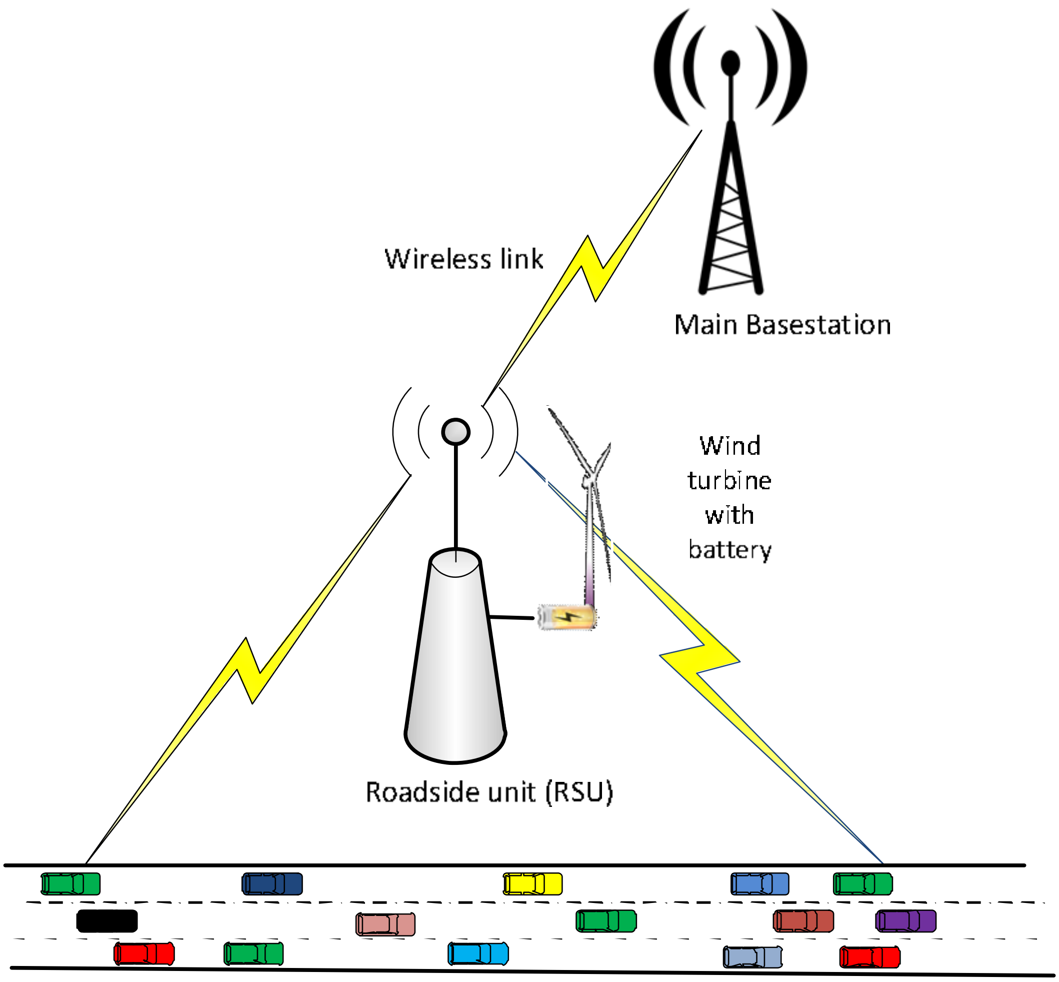

Figure 5.1: Proposed scenario.

Parameter	Notation	Value
Max. operational power	P_{RSU}	20 W [119]
Min. operational power	P_{Idle}	$\frac{P_{RSU}}{1.4}$ = 14.8 W [56]
Max transmit Power	P_{t-max}	$P_{RSU} - P_{Idle}$ = 5.2 W
Propeller length (diameter)	D	1 m [124]
Swept area	A	0.8 m^2
Air density at 15^0C	ρ	1.225 kg/m^3 [125]

Coefficient of performance	C_p	0.45 [107]
Cut-in wind speed	V_{cut_in}	3.5 m/s [108]
Cut-off wind speed	V_{cut_off}	21 m/s [108]
Mean vehicle data generation rate	d_v	320 kbps
Average packet size	P_s	867.4 Bytes
RSU max data rate	d_R	27 Mbps [3]

Table 5-1: System Parameters.

5.3 Rician Fading in a Motorway Environment

The channel fading associated with motorway communications has been described by a Rician distribution in the literatures [126]. Rician fading is similar to Rayleigh fading, except that a strong dominant component is present. This dominant component can for instance be the line-of-sight component typical in motorway communications. Since the wireless channel is unpredictable in a dynamic vehicular environment, it is imperative to incorporate the impact of its unavailability due to fading in vehicular networks. It is necessary therefore to determine the level-crossing rate (LCR) which denotes the number of fades per second, and the average fade duration (AFD) which depends upon parameters such as average received power, operating frequency, receiver sensitivity, fading statistics, and vehicle's speed [127]. The LCR for Rician fading [127] is given as

$$L_z = \sqrt{2\pi(k + 1)} f_d \rho e^{-k-(k+1)\rho^2} I_0\left(2\rho\sqrt{k(k + 1)}\right) \tag{5.1}$$

where the Rician k-factor (fading parameter) is defined as the ratio of signal power in the dominant component to the mean scattered power; f_d is the Doppler frequency, ρ is the normalised threshold and I_0 is the modified Bessel function of the first kind, zero order. The normalised threshold is given in terms of the threshold power level (P_o) and the average power level (P_r) as

$$\rho = \sqrt{P_o/P_r} \tag{5.2}$$

while the Doppler shift $f_d = (vf)/s$ where v is the velocity of vehicle, f is the carrier frequency of the transmitter and s is the velocity of light. Assuming isotropic scattering with one non-random component, the average Rician fade duration [128] is given as

$$\tau = \frac{1-Q\left(\sqrt{2\pi},\sqrt{2(k+1)\rho^2}\right)}{\sqrt{2\pi(k+1)}f_d\rho e^{-k-(k+1)\rho^2}I_0\left(2\rho\sqrt{k(k+1)}\right)} \tag{5.3}$$

where $Q(a,b)$ is the Marcum Q function.

At a transmitting frequency of 5.9 GHz and 30 m/s average speed of vehicle, the maximum Doppler shift equals 590 Hz. The average transmit power of a vehicle moving at an average speed of 30 m/s in a motorway environment is 30 dBm [126]. Furthermore, -90 dBm threshold power is required at the receiver to support communication with a channel capacity of 12 Mb/s [129]. Using these parameters an average power of -70.8 dBm is received with a normalised threshold of 0.1 at a distance of 500 m (i.e. the midpoint of adjacent RSUs). The AFD and LCR obtained from these parameters are used to compute the total period of channel outage which accounts for the level of packet loss during transmission. Considering the

Poisson distributed arrival process of the packets from vehicles with mean arrival rate λ', the combined arrival process from M vehicles follows a Poisson distribution with mean $\lambda = M\lambda'$.

The mean packet arrival rate from a vehicle can be expressed as

$$\lambda' = \frac{d_v}{P_s} = 46.1 \; pkts/s \tag{5.4}$$

where d_v is the vehicle data generation rate and P_s is the mean packet size as given in Table 5.1. For a given power threshold P_o of -90 dBm and an average received power P_r of -70.8 dBm, the normalised threshold can be obtained from (5.2) as 0.11. The AFD and LCR are obtained from (5.1) and (5.3) as 140.8 fades/s and 17.8 µs for Rician parameter $k = 3$. The mean value of Rician factor in a motorway environment is 3 dB as obtained in [130]. The total fade duration (AFD_t) in 1s can be obtained as

$$AFD_t = AFD \; LCR \tag{5.5}$$

The amount of packet loss due to fading (λ'_{loss}) in 1s can be determined as

$$\lambda'_{loss} = \frac{AFD_t}{1} \lambda' \tag{5.6}$$

The throughput to the RSU which is the effective packet arrival rate (λ_1) at the RSU is obtained as

$$\lambda_1 = \lambda' - \lambda'_{loss} \tag{5.7}$$

Table 5.2 shows the obtained analytical effective mean arrival rates and percentage packet loss associated with different threshold power and fading parameters in a motorway communication environment. As shown in the table, packet loss due to fading increases for a given power threshold, say, -90 dBm, as the Rician fading parameter k reduces. In case of severe fading where $k = 0$, the Rician LCR simplifies to Rayleigh fading LCR (L_R) as

$$L_R = \sqrt{2\pi} f_d \rho e^{-\rho^2} \quad (5.8)$$

Fading parameter k	LCR	AFD (μs)	Total FD in 1s (μs)	Power threshold (dBm)	λ_1	% Pkt loss
1	84.6	105.2	8900	-90.0	45.7	0.9
2	39.5	126.6	5000	-90.0	45.9	0.5
3	17.8	140.8	2500	-90.0	46.0	0.3
4	7.9	152.2	1200	-90.0	46.1	0.1
5	3.5	172.0	600	-90.0	46.1	0.1
7	0.7	1458.2	1000	-90.0	46.1	0.1
3	51.1	276.0	14100	-83.2	45.5	1.4
3	74.3	324.6	24100	-81.3	45.0	2.4
3	271.0	578.1	156700	-75.2	38.9	15.7

Table 5-2: Rician Fading Parameters.

5.4 System Modelling and Simulation

An M/G/1/K queue model and a Java-based simulator are employed in this section to evaluate the performance of RSU with the implementation of Rician fading feature of real motorway wireless communication channel. The first stage of the simulation process entails generating Rician received power with certain Rician parameter, say, $k = 3$ and threshold power of -90 dBm. Packets with Poisson arrivals are also generated with mean arrival rate $\lambda' = 46.1\ pkts/s$ and combined arrival rate $\lambda = M\lambda'$ which varies hourly according to vehicular density. Packets are dropped each time the received power falls below the threshold to capture the effect of fading on the packet arrivals at the RSU. The average number of lost packets and the throughputs are computed to obtain the new hourly arrival rate λ_1 which serves as the input to the RSU performance simulator of section 5.4.1.

5.4.1 Simulations Process of Wind Powered Rate Adaptive RSU

A JAVA based event-driven simulator which utilises real vehicular measurements from the M4 motorway, UK, is used to evaluate the performance of the system. The simulator comprises three classes which include Vehicle, Distributions and Main classes. The Vehicle class controls packet generation from vehicles. The Distributions class generates the packet arrival time, variable data rates and packet sizes while the Main class runs the simulation. The packet's service and waiting times are recorded and used to compute the average packet delay and service duration. The packets that arrive when the buffer size K is full are blocked and the fraction of such packets account for the packet blocking probability. The simulation runs for a period of 3600 s in microsecond steps, and the QoS parameters are calculated based on the packet timestamps and the values of the hourly variables used. The hour is then incremented and the corresponding vehicular density updated by the simulator to obtain the QoS parameters for all the hours of the day. The wind energy-based data rate distribution of the RSU obtained in [123] is also implemented in the RSU simulation process.

5.4.2 System model and QoS Metrics

The wind energy-based rate adaptive RSU whose input is the new arrival rate (λ_1) can be modelled as an $M/G/1/K$ queue. The arrival process is Poisson distributed while the RSU has a general distributed service time according to the wind energy-based data rate distribution obtained in [123]. The single server which is the RSU has a limited buffer size *K*. Since the queue has a finite capacity, packets that arrive when the buffer is full are blocked or lost. The blocking probability (P_b) which is the probability of packets being lost as a result of a full buffer, as well as throughput and delay are vital performance metrics for a finite capacity system. The QoS metrics of the RSU can therefore be computed based on the equilibrium state probability p_k obtained for $M/G/1/K$ queue in [121]. The mean queue length which denotes the total number of packets in the system is expressed as

$$N = \sum_{k=0}^{K} k\, p_k \tag{5.9}$$

The packet blocking probability (P_b) which is the probability of packets arriving at a full RSU is expressed as

$$P_b = p_K \tag{5.10}$$

The system utilisation is given as

$$U = M\lambda_1 \bar{x}(1 - P_b) \quad (5.11)$$

where $\bar{x} = 1/\mu$ is the mean service time.

The mean total time spent in the system by a packet according to Little's law [122] becomes

$$W = \frac{N}{M\lambda_1(1-P_b)} \quad (5.12)$$

5.5 Results and Discussions

5.5.1 Rate Adaptive RSU Performance

The performance of wind energy-based rate adaptive RSU is investigated in terms of packet blocking probability, average packet delay and utilisation with varying hourly load and different buffer sizes as shown in Figure 5.2 – Figure 5.4. The mean hourly arrival rate at the RSU which is the average packet arrival rate from vehicles less the packet loss rate due to fading constitutes the traffic load. As observable from Figure 5.2 – Figure 5.4, the considered performance metrics of the RSU vary according to the hourly vehicular density (load). Figure 5.2 shows the variation of the average packet delay with the hourly traffic. According to expectation, the average packet delay is highest when the RSU buffer size is highest (K=20) and lowest when K=3. With large buffer size, more packets are accommodated in the queue which implies longer waiting period for service and hence high average packet delay. This however offers the benefit of reduced packet blocking probability as seen in Figure 5.3. It is interesting to note that the system performs satisfactorily in terms of delay with a buffer size as small as 3. The performance of RSU with buffer size of 3 without fading (considering an ideal channel) which is included for comparison shows a higher average packet delay than the case of RSU with the same buffer size in a real channel. This is due to the reduced number of packets served by the RSU as a result of fading in real channel.

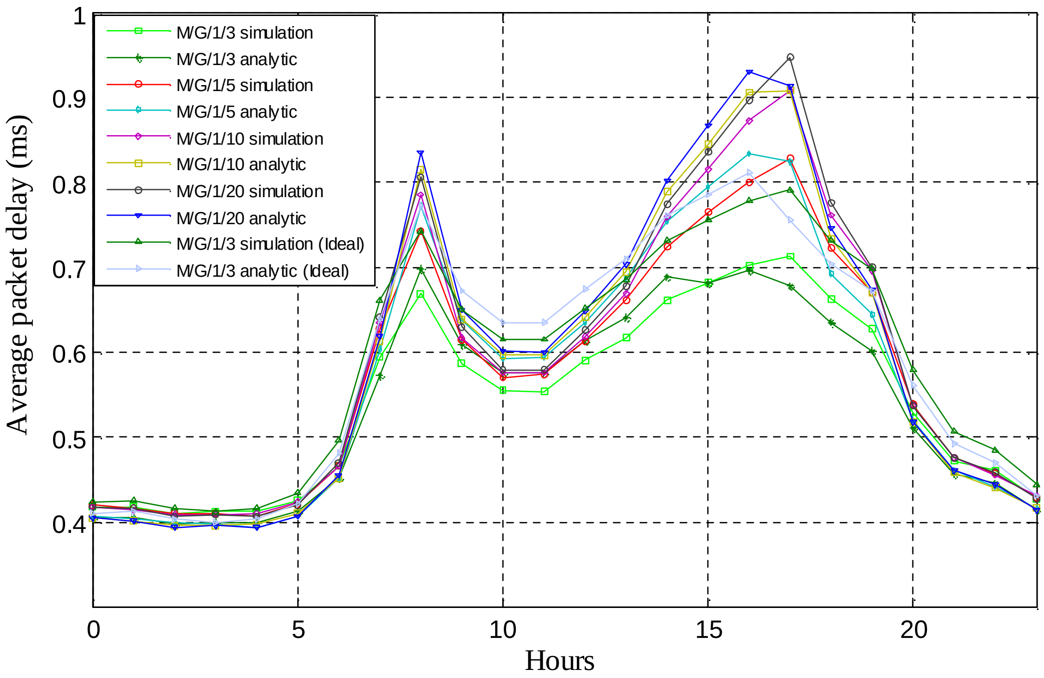

Figure 5.2: Average packet delay with varying hourly arrival rates.

Figure 5.3 shows how the PBP varies with the packet arrival rate. The buffer sizes of 20 and 10 keep the PBP mostly at zero throughout the day as the arriving packets have sufficient room in the buffer to wait for service. While the PBP with K=5 remains within the acceptable range (less than 2%) throughout the day, the two cases of buffer size of 3 with real and ideal channels have unacceptable performance with PBP approaching 4.5% and 8% respectively at some hours of the day. The blockage is mainly due to the limited capacity of the RSU which leads to buffer overflow and packet blockage after saturation.

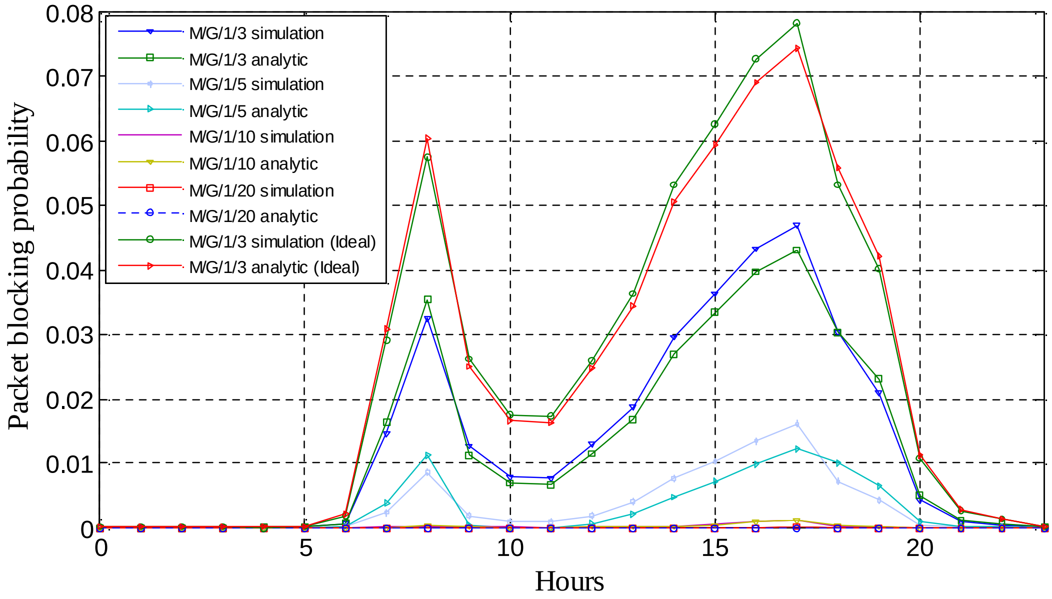

Figure 5.3: Packet blocking probability with varying hourly arrival rates.

Figure 5.4 shows the variation of system utilisation with varying packet hourly arrival rates (loads). Utilisation depends on the system capacity (buffer size K) and carried load. When K is large, the RSU would normally have a large number of packets queued up in the buffer for service which implies high utilisation. As seen in Figure 5.4, the utilisation is highest when K=20 and lowest when K=3. Furthermore, the utilisation remains low at low loads and without remarkable difference with various buffer sizes because of underutilisation. The utilisation increases with load and with noticeable difference according to the various buffer sizes.

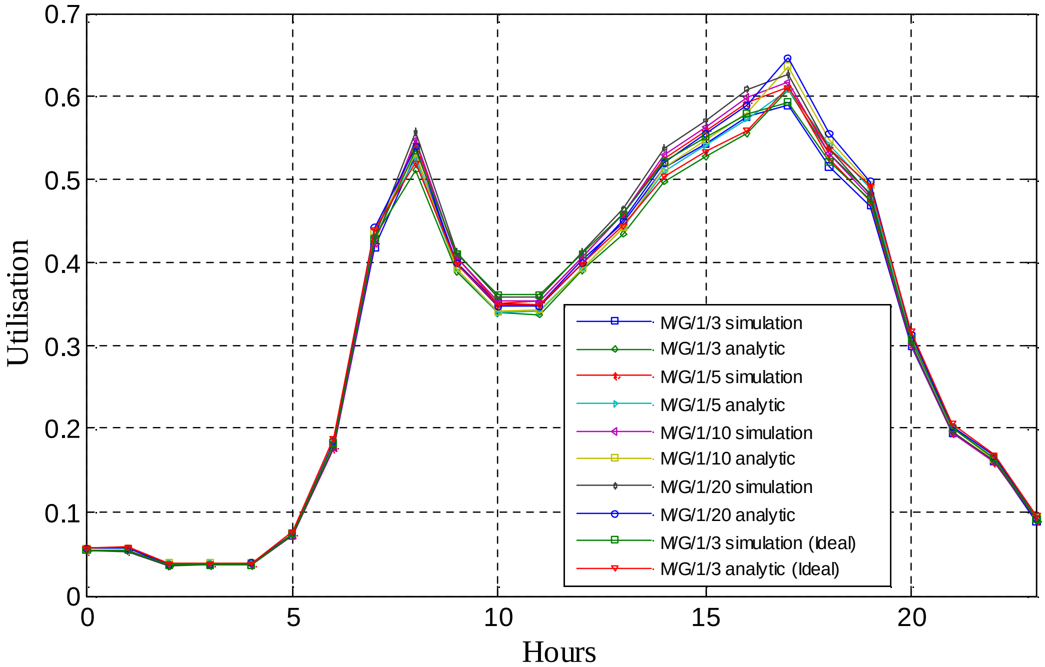

Figure 5.4: Utilisation with varying hourly arrival rates.

5.5.2 Impact of Threshold Power on QoS

As given in Equations (5.1), (5.2) and (5.3), fade duration and level crossing rate are both dependent on various parameters which include the Rician k-factor (fading parameter), operating frequency, receiver sensitivity, mean received power, threshold power, vehicle speed, etc. [127]. Noting that the level crossing rate varies directly with the normalised threshold ρ which depends directly on the threshold power P_o, the variation of basic performance metrics such as PBP, average packet delay and utilisation of the rate adaptive RSU with threshold power and traffic load according to the hours of the day are shown in Figure 5.5 – Figure 5.7. In Figure 5.5, the threshold power of -90 dBm has the highest PBP according to expectation as low threshold power, which implies low level crossing rate, indicates less fading in the channel; the RSU thus has a large number of arriving packets which increases the PBP. The highest considered threshold power of -75 dBm conversely has the lowest PBP at the RSU after a high proportion (about 15.7% according to the analysis in section 5.3) of generated packets from vehicles have been lost to fading.

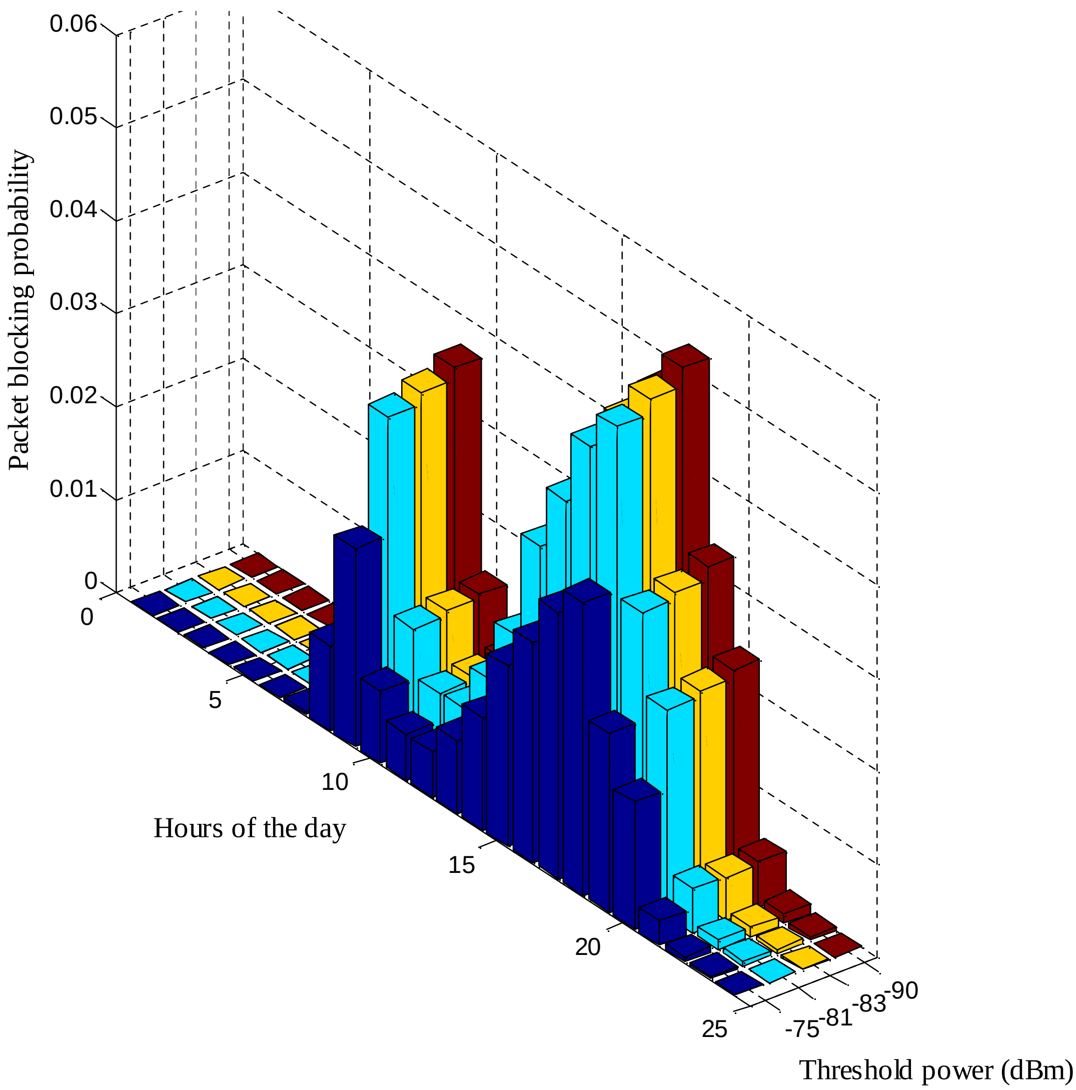

Figure 5.5: Packet blocking probability with varying threshold power and traffic load.

The average packet delay as shown in Figure 5.6 increases with decreasing level crossing rate (increasing threshold power) as there are more successfully transmitted packets from vehicles to be served by the RSU due to the reduced channel fading. The average packet delay gradually falls as the threshold power increases. The average packet delay in Figure 5.6 is fairly constant for the first five hours of the day as these hours have fairly equal average vehicular densities and traffic loads as shown in Figure 3.6 and Figure 3.9 of Chapter 3 based on the collated traffic data. The rise and fall trend closely follows the hourly traffic load trend.

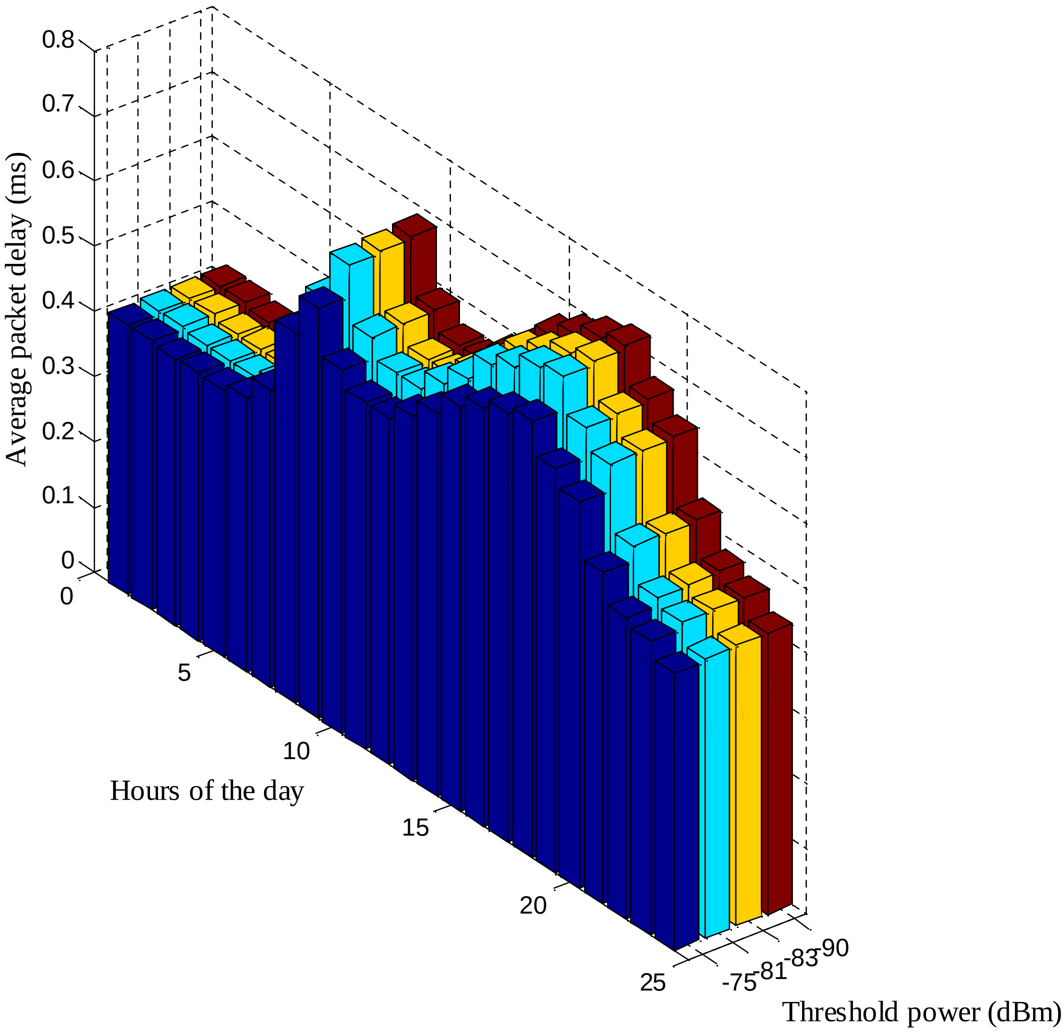

Figure 5.6: Average packet delay with varying threshold power and traffic load.

Figure 5.7 shows a steadily increasing utilisation as the carried load (served packets) increases. The number of served packets by the RSU increases as threshold power and level crossing rate decrease.

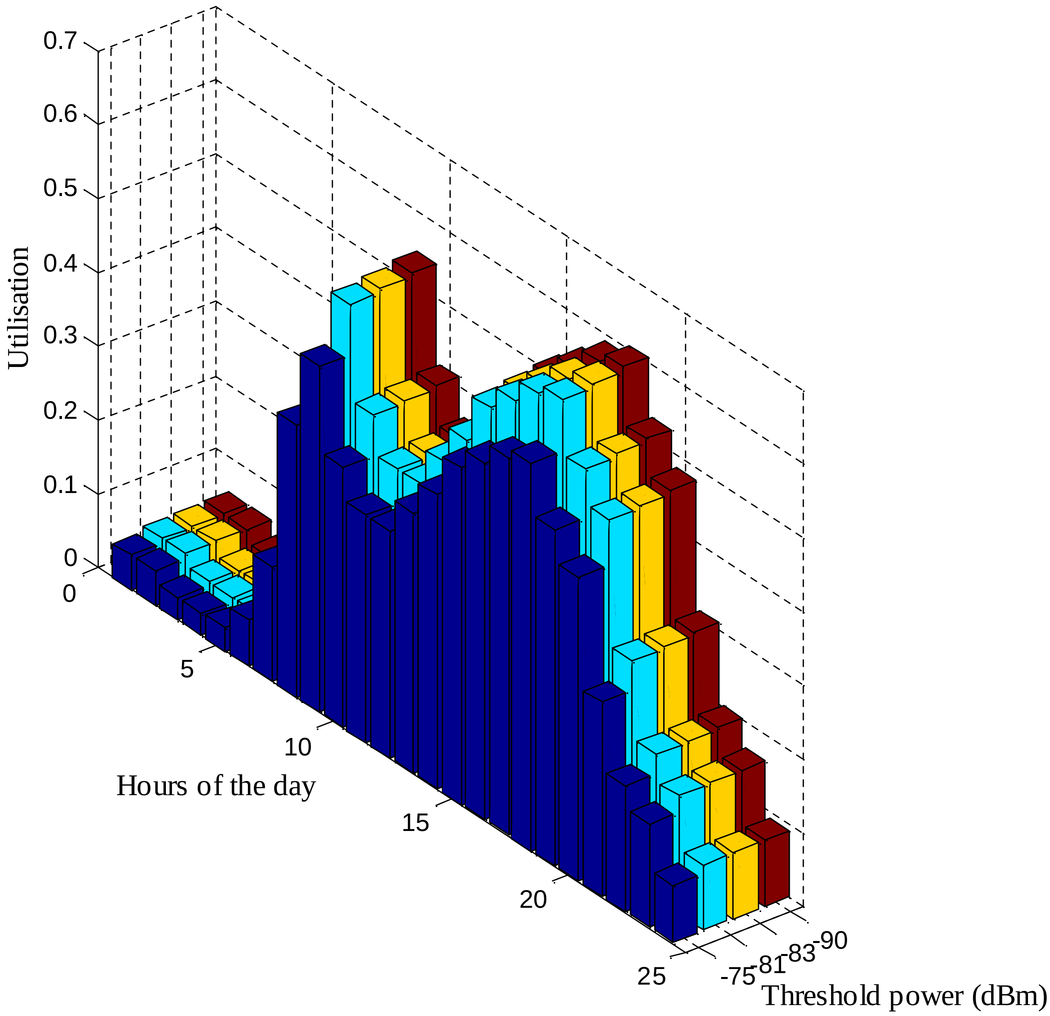

Figure 5.7: Utilisation with varying threshold power and traffic load.

5.6 Summary

The performance of wind powered rate adaptive RSU with fading in motorway vehicular networks was investigated in terms of average packet delay, system utilisation and packet blocking probability. The obtained analytic results of the queue model $(M/G/1/K)$ for the rate adaptive RSU were validated by the simulation results obtained from the event-driven Java based simulator. The effect of Rician fading on the performance of the RSU was investigated considering different threshold powers of -75 dBm, -81 dBm, -83 dBm and -90 dBm with varying hourly traffic load. The wind power- based rate adaptive RSU was found to perform satisfactorily with a threshold power of -90 dBm which is the standard power threshold requirement of 802.11p standard for vehicular communication system.

6 Reliability of Wind Powered RSU in a Motorway Vehicular Network

6.1 Introduction

This chapter is concerned with reliability study of the wind powered off-grid RSUs deployed in the vehicular networks discussed in Chapters 3 to 5. The intermittent nature of wind energy necessitates the transient study of wind powered RSU in motorway vehicular communication systems. Specifically, one needs to ensure that the renewable energy powered communication entities such as RSUs/APs are able to provide acceptable quality of service (QoS). Conventionally, reliability indices have been used to analyse fault tolerance in automated systems. In this study, the concept of fault tolerance in automated systems is redefined in the context of the availability of wind power to support the operation of off-grid wind powered RSUs in motorway vehicular environments. To investigate the reliability of the system using various indices, the RSU load model based on the measured real traffic profile of M4, and the wind energy model based on the wind data of the same region obtained for the years 2009 to 2013 from the UK air information resource (AIR) database, are used to determine the sufficiency or otherwise of the available wind energy at any time. Appropriate battery sizes are used to achieve acceptable levels of reliability in the network.

6.2 RSU Reliability Modelling and Analysis

Reliability indices are used conventionally to analyse fault tolerance of automated systems. The concept of fault occurrence in automated systems is applied here to the off-grid RSUs in the context of the availability of wind power. Reliability analysis is crucial to ascertaining the communication feasibility of an off-grid RSU considering the stochastic nature of intermittent wind speed and hence the harnessed wind power. A number of related reliability indices are therefore redefined in this section.

Following on with the probabilistic models of load and wind power obtained in Chapter 3, the reliability analysis of the RSU is now considered here. To obtain the hourly outage of the RSU (failure due to insufficient wind energy), the hourly simulated wind energy and load for a period of 5 years which is equivalent to $I = 5 \times 365 = 1825$ days are compared pair-wise [94] as

$$Outage_t = \sum_{i=1}^{I} N(E_{Wti}, E_{Lti}) \tag{6.1}$$

where

$$N(E_{Wti}, E_{Lti}) = \begin{cases} 1 & if \ E_{Wti} < E_{Lti} \\ 0 & otherwise \end{cases}$$

where I represents the total number of days. The outage is assigned a value of 1 for an hour t on day i if the generated wind energy sample value (E_{Wti}) is less than the corresponding load sample value (E_{Lti}), and 0 otherwise. The loss of load probability (LOLP) [131] in our scenario in the present context can be redefined as

$$LOLP_t = \frac{Outage_t}{I} \tag{6.2}$$

The expected loss of load over a specific time period represents another reliability index called loss of load expectation ($LOLE$). This is the average number of hours for which the load is expected to exceed the available capacity [94] and can be expressed in the present case as

$$LOLE = \frac{1}{z}\sum_{t=1}^{T}(Outage_t) \tag{6.3}$$

where z is the total number of years and T is the total number of hours in a day ($T = 24$). It signifies the average number of outage hours in a year.

To investigate the unmet capacity in the duration of study, the loss of energy expectation (LOEE) is determined. This is the expected energy in (kWh) that will not be supplied when the load exceeds the available generation, and can be derived from the hourly unmet demand in (6.1) as follows:

The unmet demand (UD_{ti}) is the amount of energy deficit at any hour t over the total number of days $(I = z \times 365)$ and can be expressed as

$$UD_{ti} = \begin{cases} E_{Lti} - E_{Wti} & if\ E_{Lti} > E_{Wti} \\ 0 & otherwise \end{cases} \quad (6.4)$$

The LOEE is the total energy not met in a year and can be obtained as yearly average for z years case study as

$$LOEE = \frac{1}{z}\sum_{t=1}^{T}\left\{\sum_{i=1}^{I}(UD_{ti})\right\} \quad (6.5)$$

The EDNS, which is the expected demand not served in an hour of the day (averaged over the 24 hours), can be obtained from the product of the state probability and the unmet demand for the hour as

$$EDNS_t = LOLP_t \frac{1}{I}\sum_{i=1}^{I}(UD_{ti}) \quad (6.6)$$

The average EDNS over a 24 hour period can be expressed as

$$EDNS = \frac{1}{T}\sum_{t=1}^{T} EDNS_t \quad (6.7)$$

The energy index of reliability (EIR) [94] indicates the energy throughput of an RSU. It is the fraction of the expected load served to the total demand as applied to our study scenario:

$$EIR = 1 - \frac{LOEE}{E_0} \tag{6.8}$$

where E_0 is the energy demand of the RSU over the whole year. The energy index of unavailability which is the complement of EIR can be expressed as

$$EIU = \frac{LOEE}{E_0} \tag{6.9}$$

The definitions of the various reliability indices used in this section are summarised in Table 6.1

Reliability Index	**Definition**
$Outage_t$	The number of times wind power is less than load in a given hour t.
$LOLP_t$	Loss of load probability at hour t is the probability of wind power being less than load for the hour.
$LOLE$	Loss of load expectation is the number of times there is an outage in a year.
$LOEE$	Loss of energy expectation is the amount of energy not supplied/met in a year.
$EDNS_t$	Expected demand not served in an hour t is the product of state probability and the unmet demand for the hour.
EIR	Energy index of reliability is the proportion of energy requested that has been met.
EIU	Energy index of unavailability is the proportion of energy requested that has not been met.
FOR	Forced outage rate is the proportion of average outage time.

Table 6-1: Definitions of reliability indices

6.3 Analytic Models for LOLP, LOLE, LOEE, EDNS, MTBF, MTTR and FOR

The quantities of interest in Table 6.1 rely mainly on determining the probability that the load power is greater than the available wind power. Hence, the analytic models of the above reliability indices can be obtained from the probability density functions of wind energy and load. The instantaneous transmission energy consumption by the RSU follows a Normal distribution with mean (μ) and variance (σ) according to the vehicular density. This is because the transmission energy consumption by the RSU equals the traffic load or energy demand (as obtained in Chapter 3) which directly depends on the product of traffic density and energy per bit. Packet arrivals are Poisson distributed, however energy per bit is evaluated over a very short time period and is approximated as Gaussian random variable. The Gaussian distribution is an excellent approximation of a Poisson distribution when the total number of events becomes sufficiently large [117]. The instantaneous wind power follows a Weibull distribution as shown in chapter 4. The pdfs of wind power and the RSU power demand (load) can be expressed respectively as

$$w(x) = \frac{\beta}{\alpha}\left(\frac{x}{\alpha}\right)^{\beta-1} e^{-\left(\frac{x}{\alpha}\right)^{\beta}} \qquad x \geq 0 \tag{6.10}$$

and

$$l(y) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{\left((y-P_{Idle})-\mu\right)^2}{2\sigma^2}} \tag{6.11}$$

The $LOLP_t$ which represents the probability of failure, i.e., the probability that wind power is less than or equal to load can be expressed as

$$LOLP_t = Prob\big(w(x) \le l(y)\big) \tag{6.12}$$

Hence,

$$LOLP_t = \int_{P_{\mathrm{Idle}}}^{P_{\max}} \left\{ \int_0^y w_t(x)dx \right\} l_t(y)dy \tag{6.13}$$

where $w_t(x) = \frac{\beta_t}{\alpha_t}\left(\frac{x}{\alpha_t}\right)^{\beta_t-1} e^{-\left(\frac{x}{\alpha_t}\right)^{\beta_t}}$; $l_t(y) = \frac{1}{\sigma_t\sqrt{2\pi}} e^{-\frac{\left((y-P_{Idle})-\mu_t\right)^2}{2\sigma_t^2}}$ and P_{max} is maximum power demand (load). Substituting (6.10) and (6.11) in (6.13), (6.13) becomes

$$LOLP_t = \int_{P_{\mathrm{Idle}}}^{P_{\max}} \left\{ \int_0^y \frac{\beta_t}{\alpha_t}\left(\frac{x}{\alpha_t}\right)^{\beta_t-1} e^{-\left(\frac{x}{\alpha_t}\right)^{\beta_t}} dx \right\} \frac{1}{\sigma_t\sqrt{2\pi}} e^{-\frac{\left((y-P_{Idle})-\mu_t\right)^2}{2\sigma_t^2}} dy \tag{6.14}$$

Integrating the integrand in the bracket according to [132], (6.14) becomes

$$= \int_{P_{\mathrm{Idle}}}^{P_{max}(t)} \left(1 - e^{-\left(\frac{y}{\alpha_t}\right)^{\beta_t}}\right) \frac{1}{\sigma_t\sqrt{2\pi}} e^{-\frac{\left((y-P_{Idle})-\mu_t\right)^2}{2\sigma_t^2}} dy$$

Since solving the above integral is not possible analytically, if we are interested in worst case hourly failure probability ($LOLP_t$), then this occurs at $y = P_{max}$ in which case $y = P_{max}$ and $l_t(y) = 1$.

Hence,

$$LOLP_t = 1 - e^{-\left(\frac{P_{\max}}{\alpha'_t}\right)^{\beta'_t}} \tag{6.15}$$

$LOLE$ can be expressed analytically in terms of $LOLP_t$ obtained in (6.15) as

$$LOLE = \frac{1}{z} \sum_{t=1}^{T} (LOLP_t\ I) \tag{6.16}$$

Similarly, the model for the LOEE, which represents the average unmet demand in a year, can be obtained as the product of failure probability and the total energy demand in a year as

$$LOEE = E_0 \frac{1}{T} \sum_{t=1}^{T} LOLP_t \tag{6.17}$$

where E_0 is the total load demand in a year.

$EDNS_t$, the unmet energy in an hour, can also be expressed analytically as

$$EDNS_t = LOEE_t LOLP_t \tag{6.18}$$

where $LOEE_t = \frac{1}{I} \sum_{i=1}^{I} UD_{ti}$.

The unavailability of sufficient wind power causes the RSU to fail. It remains non-operative until the available wind power becomes higher than the load energy. The corresponding down time duration is represented as time to recover (TTR). Similarly, the up time duration during which the RSU remains operative (till the RSU fails) is represented as time before failure (TBF), as shown in Figure 6.1.

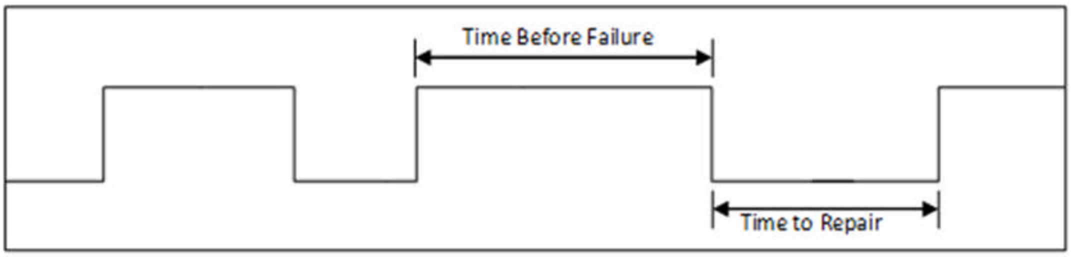

Figure 6.1: Reliability timing diagram of the RSU.

The average values of TTR and TBF over a certain duration can be defined as mean time to recover (MTTR) [133] and mean time before failure (MTBF) [133], which can be derived from the probability density functions of failure and recovery times obtained from wind and load energy samples. The reliability or survival rate function $R(t)$ of a Weibull distribution $f(t)$ [134] can be expressed as

$$R(t) = 1 - F(t) = e^{-\left(\frac{t}{\alpha}\right)^{\beta}} \tag{6.19}$$

where $F(t)$ is the cumulative distribution function (CDF) of $f(t)$. The hazard or failure rate $h(t)$ is the probability of failure at time Δt given that it has worked until time t. This can be written as

$$h(t) = \frac{f(t)}{R(t)} = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}. \tag{6.20}$$

The time before failure (TBF) function is the reciprocal of the failure rate which is given as

$$TBF(t) = \left(\frac{1}{h(t)}\right). \tag{6.21}$$

The mean time between failures (MTBF) can be obtained by taking expectation of $TBF(t)$ over time t ranging from 0 to ∞.

The downtime pdf $D(t)$ can be expressed as the probability that the wind power is less than the load power for any given value of load power for the duration of time t. Therefore, it is the complement of the reliability function and is expressed as

$$D(t) = 1 - R(t) = F(t) \tag{6.22}$$

Time to repair can be expressed as

$$TTR(t) = {}^{1}\!/_{D(t)} \tag{6.23}$$

The mean time to repair (MTTR) can be obtained by taking expectation of TTR(t) over time t to ∞. The forced outage rate (FOR) can be expressed in terms of MTTR and MTBF [135] as

$$FOR = \frac{MTTR}{MTBF + MTTR} \tag{6.24}$$

6.4 Results and Discussions

The proposed model for $P_w - P_L$ is validated by its good agreement with the simulation result as shown in Figure 6.2. Figure 6.2 shows the dominance of wind power over load on hourly aggregate with the peak dominance being at the noon. The pdf of positive $P_w - P_L$ is shown in Figure 6.3 while Figure 6.4 shows the pdf of negative $P_w - P_L$. The energy deficit and surplus levels of the

RSU have been obtained from the energy consumption and wind energy models. The hourly surplus/deficit energy is obtained by subtracting the hourly energy demand from hourly wind energy. The positive and the negative values obtained for 1825 hourly samples are used for the probability density plots in Figures 6.3 and 6.4.

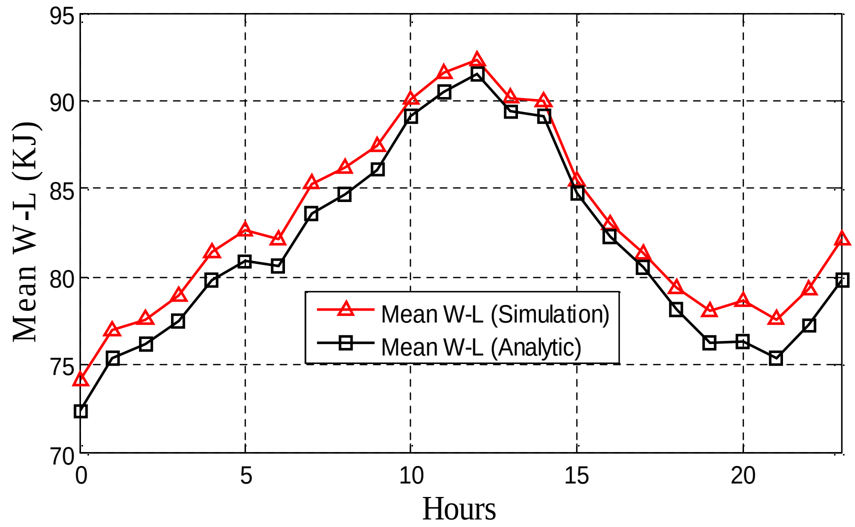

Figure 6.2: Hourly mean $P_w - P_L$.

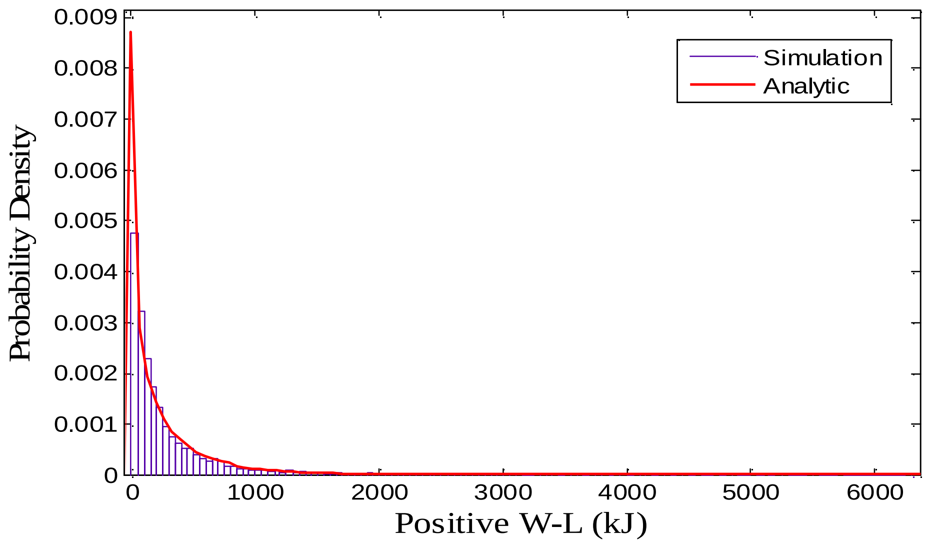

Figure 6.3: Probability density function of instantaneous (positive) $E_w - E_L$.

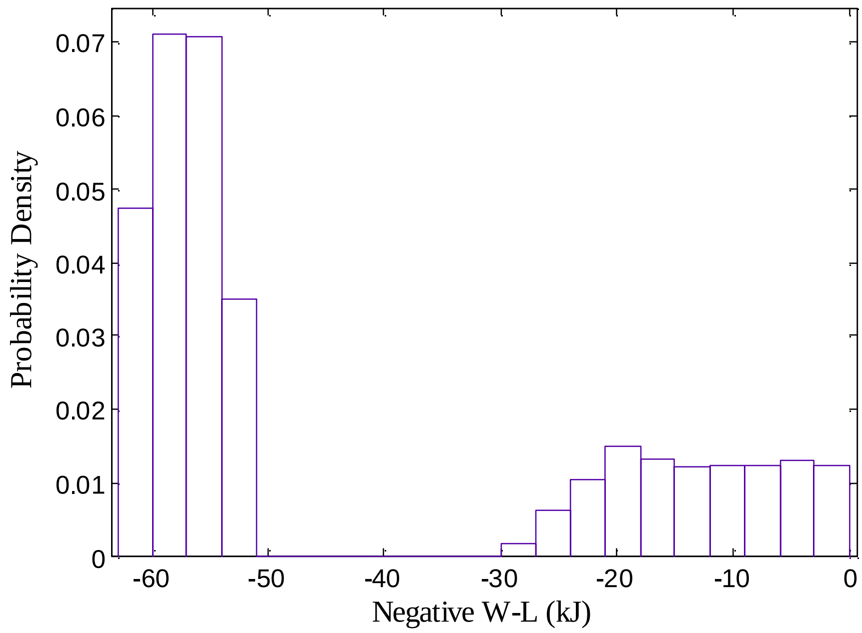

Figure 6.4: Probability density function of instantaneous (negative) $P_w - P_L$.

It is clear from Figures 6.3 and 6.4 that there are number of instances where the wind energy is insufficient to keep the RSU operational. The computation of surplus/deficit energy from a sample size of 43800 reveals 36.9% energy deficiency (negative $P_w - P_L$) and 63.1% energy surplus (positive $P_w - P_L$). As seen in Figure 6.4, deficits beyond -30 kJ (i.e. -50 kJ to -72 kJ) refer to the unavailability of wind energy due to very low (i.e. less than cut-in) wind speed. The deficit that occurs from the moment the wind speed attains the cut-in speed of 3.5 m/s and above is shown between -30 kJ and 0 kJ as the turbine now functions. There is no deficit between -30 kJ and -50 kJ as the minimum load energy which constitutes the deficit when the turbine has zero output is 54 kJ. The high percentage surplus energy realised can be stored to meet the incurred deficit.

With the surplus energy being almost twice the deficit energy, the additional surplus energy after meeting the deficit via battery can be disregarded as it cannot be injected back into the grid (RSU is off-grid standalone). This is to prevent the continuous buildup of surplus energy and limit the size of battery for the standalone RSU. Moreover, determining the required battery size for a given communication demand is crucial for the ease of deployment. Thus the battery with minimum capacity should be able to cater for the maximum deficit at any point in time during the whole day. The instantaneous cumulative energy level can be obtained as

$$C = C' + (P_w - P_L) \tag{6.29}$$

where C denotes the current energy level and C' denotes the previous energy level in the battery, and is set to an initial value of 0 kJ. E_W and E_L represent the generated instantaneous wind (i.e. available) and load (i.e. demand) energies, respectively. To determine the maximum discharge level (i.e. deficit), we disregard the surplus energy by placing a ceiling as $C = 0$. The resulting maximum discharge level of -637 kJ obtained for the studied scenario requires a maximum battery of size 29.4 Ah (considering a 12 V deep cycle battery with a 50% depth of charge (DOD) [136]). However to determine the minimum battery size which facilitates a certain level of reliability and QoS, the cumulative discharge level needs to be converted into the probabilistic domain by obtaining cumulative probability plot for the discharge behavior.

Having determined the battery sizes for 96% and 99.9% availabilities as 7.9 Ah and 22.7 Ah respectively, the performance of the RSU is evaluated with respect to key reliability indices for the three cases: I) No battery, II) 7.9

Ah battery, and III) 22.7 Ah battery. The respective analytical models are verified with simulation. The battery sizes of 7.9 Ah and 22.7 Ah yield 96% and 99.9% availabilities respectively.

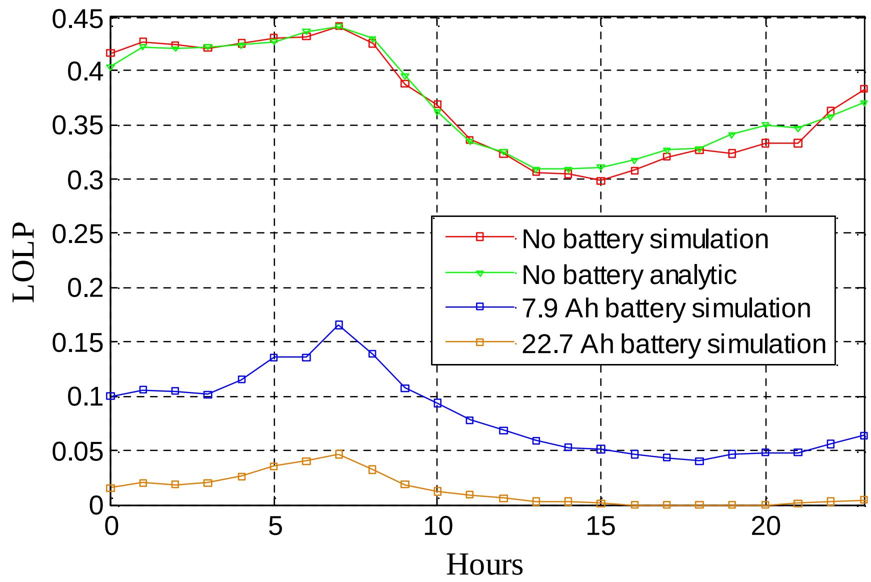

Figure 6.5: LOLP of the RSU with and without battery.

Figure 6.5 shows the hourly probability of failure (LOLP) (both simulation and analytic results) for the three cases: I) No battery, II) 7.9 Ah battery and III) 22.7 Ah battery against the hours of the day. As expected, in the case of no battery, the LOLP is very high (i.e. up to 0.44) at some hours of the day. This is due to the relatively low wind energies (see Figure 3.3) compared to the load demands (Figure 4.2) at those hours, thus, necessitating the need for integrating a battery. During midday the load demand increases, however the wind energy increases substantially resulting in a much lower LOLP even without a battery. The LOLP for the RSU with no battery remains relatively high, ranging between 0.30 and 0.44. A 7.9 Ah battery enabling 96% availability lowers the LOLP to a range below 0.1 for most hours of the day while 22.7 Ah battery which presents 99.9% availability keeps the LOLP at 0 for most hours of the day.

While the hourly LOLP represents the shortage probability, the EDNS signifies the amount of shortage. Thus the hourly EDNS (Figure 6.6) exhibits a similar trend as that of hourly LOLP (Figure 6.6). The hourly EDNS in the case with no battery has a peak of 9.35 kJ at 0800 hrs with a minimum of 4.12 kJ at 1600 hrs. The EDNS for the cases with batteries are significantly low as expected. For example, the 7.9 Ah battery lowered the EDNS to a maximum of 1.28 kJ while 22.7 Ah battery maintained EDNS around 0 kJ for most of the day.

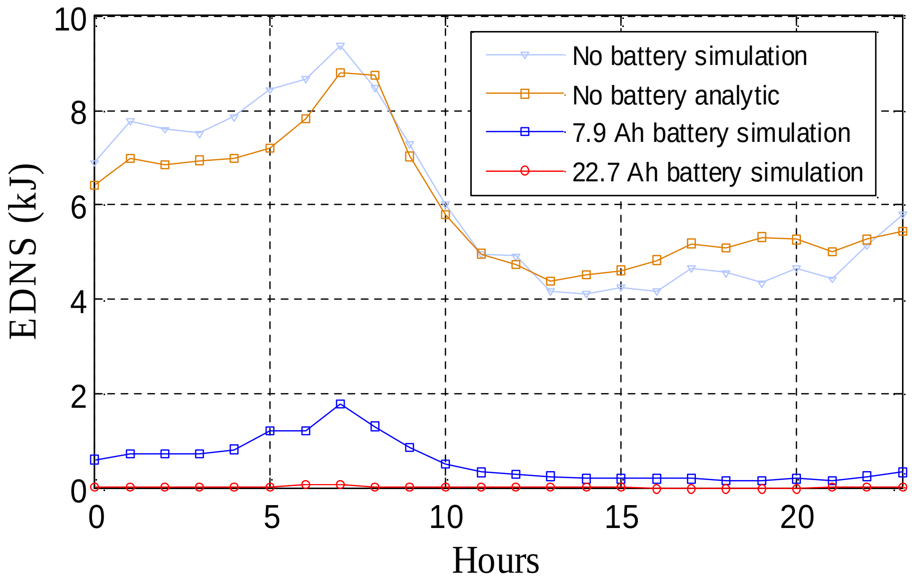

Figure 6.6: EDNS with and without battery.

To determine FOR, the MTBF and MTTR are obtained by taking samples of uptimes and downtimes of the RSU. These are used to obtain distributions of time between failures and time to recover, as shown in Figure 6.7 and Figure

6.8, respectively. Figure 6.7 shows the survivor function of the time between failures for all the four cases. The survivor function, also known as a survival function or reliability function, is a property of any random variable that maps a set of events (in this case failure of an RSU), onto time. It indicates the probability of a system or unit surviving until a given time, i.e. time before failure in this application. The various time limits (in hours) the RSU can function reliably or survive is shown against the probability of reliability as survivor function. The RSU with no battery (i.e. case I) only lasts a maximum of 20 hours before a failure. Case II (with 7.9 Ah battery) can provide continuous operation of up to 500 hours while case III (with 22.7 Ah battery) achieves a maximum of 35,000 hours of uninterrupted service. The analytic models of the survivor function for the three RSU cases have good agreement with the simulations (all following Weibull distribution) according to the analytic models obtained for the probability density function of RSU failure in sections 6.3. As expected in all reliability parlance, the survivor function approaches zero as age (mean time before failure in this case) increases without bound.

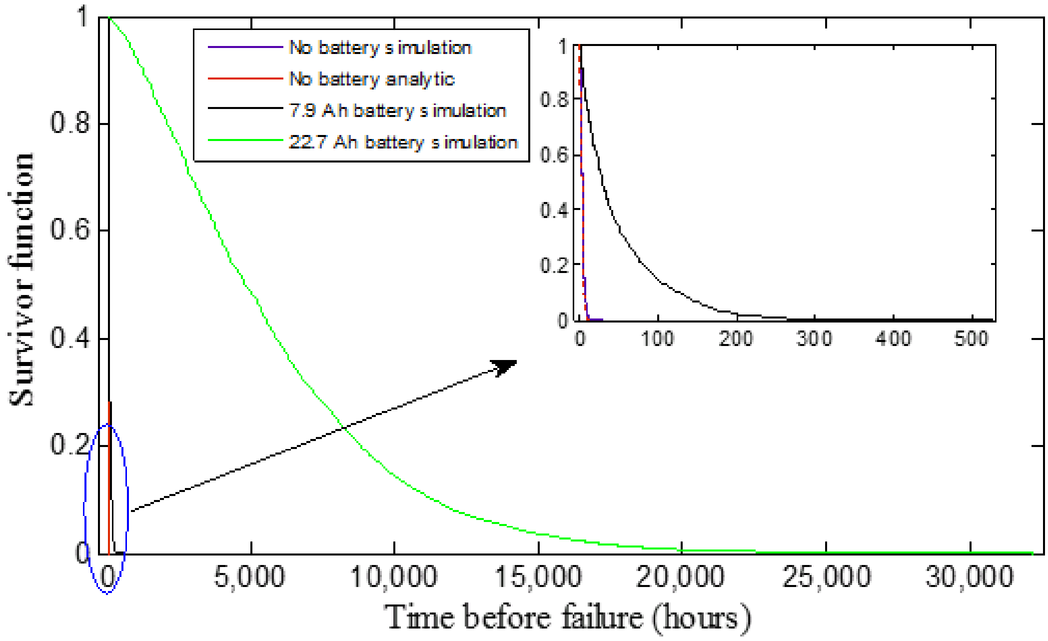

Figure 6.7: Time before failure (TBF) with and without battery.

The simulation result of the time to recover, as in Figure 6.8, shows that recovery time for all cases (with and without batteries) is primarily between 1 to 2 hours, reaching up to 11 hours rarely. Although all the cases exhibit very similar recovery times, inclusion of a larger battery moves the curves in Figure 6.8 up, i.e., the probability of the system recovering within say 4 hours is a higher probability (area under curve) if a larger battery is used.

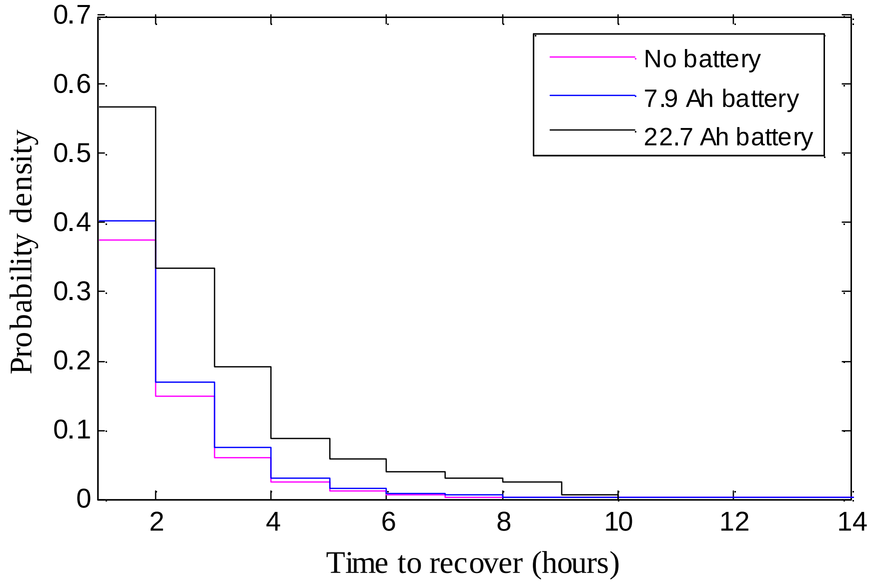

Figure 6.8: Time to recover (TTR) pdf with and without battery.

The overall reliability of the RSU is analysed using the LOLE, EIR, EIU and FOR as shown in Figure 6.9. The LOLE without a battery is 36.9% which corresponds to the percentage of energy deficit. This is expected since the loss of load is caused by energy deficiency. Hence the probability of such energy deficiency is equivalent to the LOLE. A 7.9 Ah battery brings the LOLE down to 8.3% while 22.7 Ah achieves a very low LOLE of 1.4%. The EIR without battery subsequently has lower value (i.e. 72%) compared to the 89.9% with a 7.9 Ah battery and even higher (99%) with a 22.7 Ah battery. The unavailability index (EIU) attains 28.1% with no battery while the cases of 7.9 Ah and 22.7 Ah battery-equipped RSU are limited to 10% and 1.3% EIU, respectively. These are all due to the fact that less RSU failure or outage occurs with increased energy supply from wind and battery of relatively larger sizes.

The MTBF predicts the average uptime whereas the MTTR predicts the average duration of outages. The MTBF and MTTR are used to determine the FOR in (6.24). As shown in Figure 6.9 the integration of a battery with the RSU significantly improves the MTBF, whereas the improvement in MTTR is marginal as recovery is independent of a battery size. As expected, FOR is highest for the no battery case. Battery addition reduces the FOR from 27% to 2.1% and 0.02% respectively with 7.9 Ah and 22.7 batteries. These are once again due to the fact that less RSU failure or outage occurs with increased energy supply from wind and relatively larger size battery. The MTBF is hence improved, leading to a reduced forced outage rate.

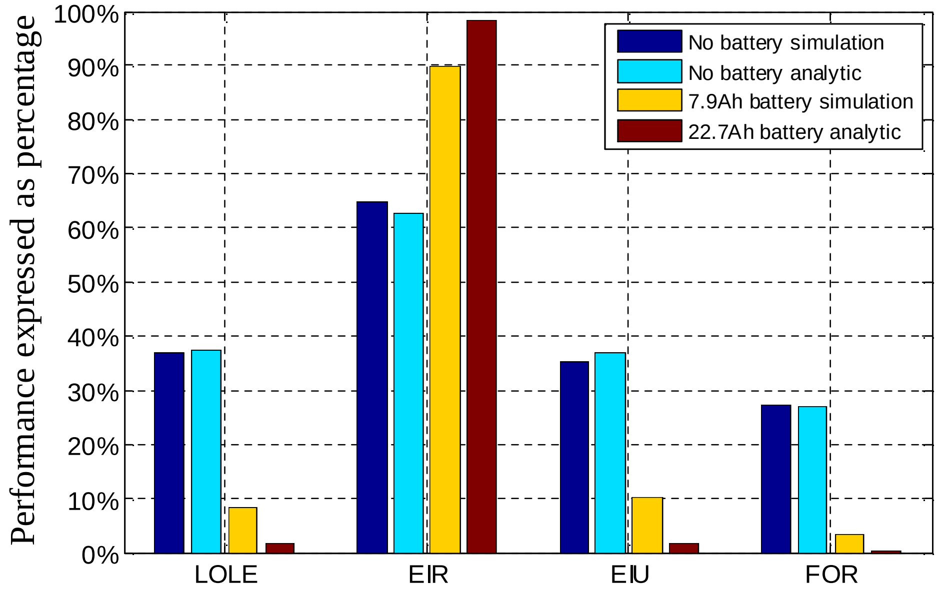

Figure 6.9: Overall performance of the RSU.

Finally, the QoS of the RSU is evaluated in terms of packet dropping (or blocking) probability, average packet delay and throughput while considering the RSU as a queue with an infinite buffer. The real channel impairments are ignored in this analysis for the purpose of investigating the performance of the RSU in the context of its energy supply only. The assumption of RSU having infinite buffer is not far-fetched as modern access points can be equipped with large memory such as embedded multimedia card (EMMC) [137]. Since the RSU has an infinite buffer, the packets are only lost (blocked) due to the unavailability of the RSU. Hence, the LOLP is the packet dropping (blocking) probability. Having already obtained the packet dropping probability (i.e. LOLP), we now determine the average packet delay at the RSU.

A typical grid connected RSU serves all packets at the maximum data rate (d_r). However, the RSU in our case drops all the arriving packets during its down time (when unavailable). To determine the throughput and the average packet delay for the successfully transmitted packets, the RSU is modelled as an *M/M/1* queue [138] where the first *M* represents the Poisson arrival of the packets from the vehicles, second *M* refers to the service rate and 1 denotes the number of server (i.e. RSU transmitter). Thus, the hourly average packet delay W_t can be obtained from the response time expression of an *M/M/1* queue [122] as

$$W_t = \frac{1}{\mu - M\lambda_t(1 - LOLP_t)} \tag{6.30}$$

where M refers to the hourly density of vehicles. Figure 6.10 shows the average packet delay against the hours for the three cases of no battery (case I), 7.9 Ah battery (case II) and 22.7 Ah battery (case III). The values of M, the arrival rate (λ_t) and the service rate (μ) used in this computation are obtained from the vehicular traffic profile of Chapter 3. The average packet delay is relatively low in all the cases with the values ranging between 0.26 ms and

0.45 ms. The average packet delay is lowest in case I due to the less number of packets awaiting service in the buffer after a significant packet loss arising from high $LOLP_t$. The reduced $LOLP_t$ in cases II and III resulted in a slightly higher average packet delay as the buffer now has an increased number of waiting packets to be served by the RSU.

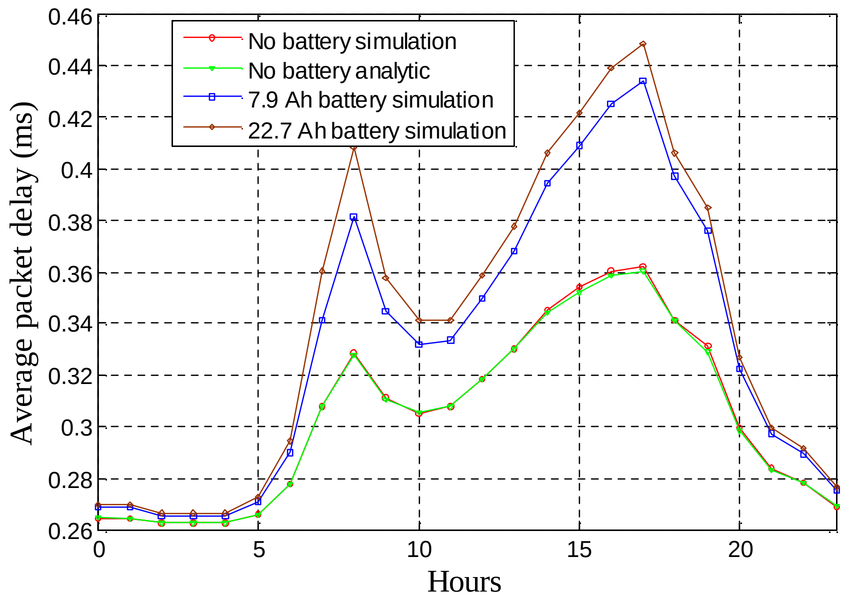

Figure 6.10: Average packet delay of the RSU.

Similarly, the hourly throughput (X_t) of the RSU can be obtained as

$$X_t = M\lambda_t(1 - LOLP_t) \tag{6.31}$$

As shown in Figure 6.11, the average throughput of the RSU varies inversely with the $LOLP_t$ as expected. The case I with no battery which has the highest $LOLP_t$ portrays the lowest throughput at all time. This is evident from the fact that many packets were dropped by the RSU during its periods of unavailability. The two cases with different battery sizes show improved throughput with the 22.7 Ah battery having the highest (1500 packets/s). The two peak values in both Figure 6.10 and Figure 6.11 at hours 8.00 and 17.00

are in conformity with the peak vehicular flow and density at such busy hours of the day.

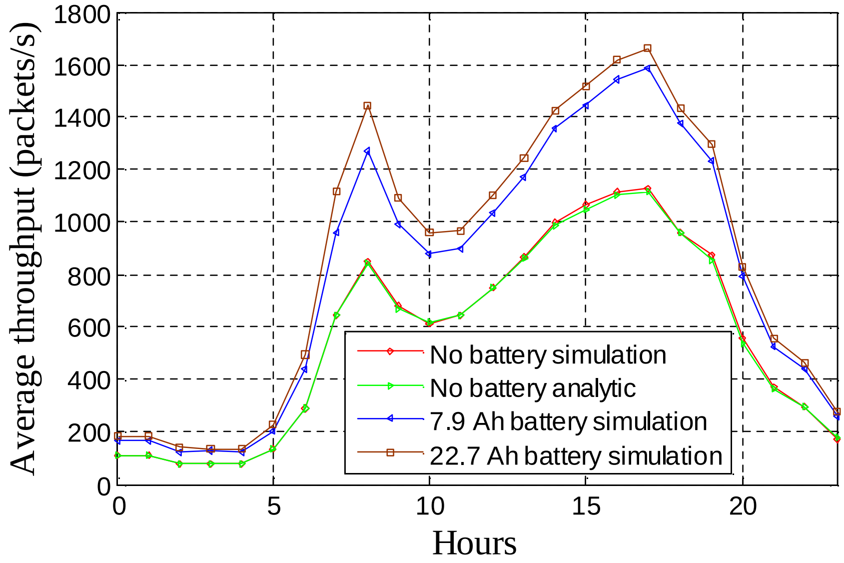

Figure 6.11: Average throughput of the RSU.

6.5 Comparison with other Windy and Non-Windy Locations

The hourly wind speed data for different US cities (San Franciso, Berkeley, Boston and Galveston) for a period of 5 years [139] were obtained and the instantaneous wind energies were generated at each location through the wind model. To represent vehicular traffic of these cities, an hourly vehicular densities from I-80 inter-state expressway [140] were obtained and the instantaneous load energies were generated through the load model.

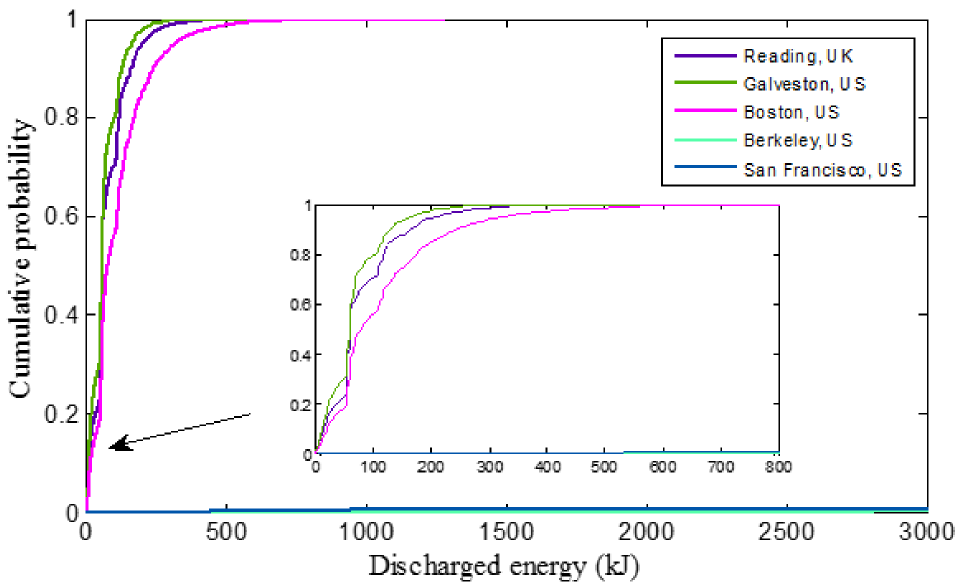

Figure 6.12: Comparative cumulative probability of discharged energy.

Figure 6.12 compares the cumulative deficits of the various cities investigated. The x-axis represents the cumulative deficit while y-axis is the probability that the cumulative deficit is less than say 500 kJ. From the computation of total surplus/deficit energy based on the source data, it is found that locations such as San Francisco and Berkeley in the US do not have sufficient wind speed and the yearly average deficit indicates acute wind energy shortages i.e. 27 kWh and 47 kWh, respectively where a single RSU is considered. Therefore, integrating an energy-storage (e.g. fast rechargeable battery) will be meaningless since the battery will be unable to recharge due to the insufficient wind energy in such locations. However, windy locations in the US such as seaside Galveston and I-80 stretch near Boston are found to have on average yearly surplus wind energy i.e. 380 kWh and 195 kWh while the main city of study interest (Reading, UK) has enough yearly wind energy i.e. 412 kWh average yearly surplus.

As discussed before, the continuous deficit of wind energy results in very large cumulative discharged energy in non-windy locations such as San Francisco and Berkeley (see Figure 6.12). Therefore, any battery size would be insufficient (given our RSU and wind turbine parameters, and wind speeds) in these locations due to the lack of wind energy required for recharging. However, significantly lower battery sizes are required in windy locations like Reading (UK) and Galveston compared to Boston. Considering a 12 V deep cycle battery with a 50% *depth of discharge* (DOD) [136], a battery size of 28.8 Ah is required in Galveston compared to 59 Ah in Boston to completely eradicate outage while in Reading, UK, a battery size of 29.4 Ah is needed. The respective maximum battery sizes for the various cities were obtained from their maximum cumulative discharged energies which are 637 kJ, 623 kJ, 1277 kJ, 479100 kJ and 851095 kJ for Reading, Galveston, Boston, San Francisco and Berkeley respectively. The battery size in general can further be reduced if a certain percentage of outage is allowed. However, this requires further in depth analysis with the help of the discussed reliability indices.

6.6 Summary

In this chapter, we carried out transient analyses of energy consumption of an RSU and harnessed wind energy from a micro-turbine for that RSU in a motorway vehicular environment. Subsequently we proposed corresponding analytic models. Furthermore, we proposed analytic model for obtaining the minimum battery size for achieving certain levels of reliability and QoS. The main thrust of this work is to redefine and model usual reliability indices in the context of intermittent availability of wind power in vehicular communications. The transient models and the reliability analyses proposed in this thesis are generic and can be used for any location, where the need for fast and standalone RSU deployment is of paramount importance.

Considering the M4 motorway vehicular environment as a study scenario, we evaluated the performance of a wind powered RSU in terms of reliability indices such as loss of load probability, expected demand not served, loss of load expectation, energy index of reliability and forced outage rate, and QoS parameters such as average packet delay and throughput. The forced outage rate of 27% with no battery was brought down to only 0.03% with a battery of size 22.7 Ah. Similarly, the loss of load probability was reduced to 0.009 (almost zero) with a 22.7 Ah battery, compared to the case of no battery where the loss of load probability was 0.44 at some hours of the day. The results revealed that the RSU was able to achieve 90% and 99% reliabilities with 7.9 Ah and 22.7 Ah batteries, respectively. The achieved reliability is good compared to the industrial standard reliability (99.9% or 99.999%) which is maintained with adequate resource provisioning. Furthermore, the RSU achieved an acceptable average packet delay (between 0.26 ms and 0.45 ms) for all the cases studied and equally showed an improved throughput of up to 50% with the lesser battery size considered in the study.

7 Conclusions and Future Work

7.1 Conclusions and Key Findings

This thesis aims to address some of the challenges confronting ubiquitous network connectivity in motorway vehicular communication systems by proposing economical and easy to deploy alternative (renewable) energy supplies in the dispersed network environments. Various energy efficient strategies that optimise the usage of the renewable energy sources are employed while stringent QoS criteria are satisfied. Besides the economic benefit of this approach, a purely renewable energy powered Aps/RSUs also addresses the carbon footprint concern of vehicular communication systems. A high level of realism is maintained in the thesis by using realistic measured data as inputs to the analyses and simulations carried out.

A detailed statistical analysis of measured vehicular traffic data of the M4 motorway in the UK was carried out to understand the traffic flow, density, speed and inter-arrival time patterns. These analyses have been used to generate the instantaneous traffic load that constitute energy demand at the RSUs as well as mobility simulator that reflects real vehicular movement.

With the primary aim of deploying renewable energy resource which reduces carbon foot print the use of wind energy for the motorway RSUs has been proposed. In order to develop a model for the harnessed wind energy from a micro-turbine, a detailed analysis of wind energy has been carried out using the hourly average wind speed samples at the RSU site which were obtained from the UK air information resource (AIR) database for a period of five years. The samples were used to obtain the hourly probability distribution of wind speed which follow a Weibull distribution. The intermittent nature of wind energy has also necessitated an in-depth reliability study of wind powered RSU as a standalone entity to investigate the adequacy of available wind power to support the high quality service requirement of vehicular communication system in an off-grid motorway environment at every point in time. Conventionally, reliability indices have been used to analyse fault tolerance in automated systems. In this study, the concept of fault tolerance in automated systems was redefined in the context of the availability of wind power to support the operation of an off-grid wind powered RSUs in motorway vehicular environments. The results revealed that the RSU was able to achieve 90% and 99% reliabilities with 7.9 Ah and 22.7 Ah batteries respectively. Moreover, the RSU forced outage rate of 27% with no battery was brought down to only 0.03% with a battery of size 22.7 Ah.

For the purpose of maximising the usage of the renewable energy sources and improving the power margin of vehicular networks, a wind energy dependent rate adaptive RSU that provides ubiquitous coverage along a motorway stretch was proposed and implemented in vehicular networks. Analytic models for both wind energy and real vehicular traffic energy demand were used to develop the adaptive data rate algorithm for RSUs in motorway vehicular networks. The performance of the modelled and simulated wind energy based adaptive rate RSU was investigated in terms of consumed transmission energy, average packet delay and packet blocking probability. The proposed wind power-based rate adaptive technique reduced the system outages by providing improved spread of data rates as against the mainly 0 and 27 Mbps data rates of non-rate adaptation scheme. With the rate adaptive algorithm, the RSU has a service outage of only 1% (which represents 99% service availability) while in the two cases of non-rate adaptation, the service outages are 34% and 8% for the wind energy only and wind energy with battery respectively. The proposed wind powered rate adaptive RSU offered a power margin of 23% when compared with a non-rate adaptive RSU while satisfying the required service quality.

Furthermore the performance of wind powered rate adaptive RSU with fading in motorway vehicular networks was investigated in terms of average packet delay, system utilisation and packet blocking probability. The obtained analytic results of the queue model $(M/G/1/K)$ for the rate adaptive RSU were validated by the simulation results obtained from the event-driven Java based simulator. The effect of Rician fading on the performance of RSU was investigated considering different threshold powers of -75 dBm, -81 dBm, -83 dBm and -90 dBm with varying hourly traffic load. The wind power- based rate adaptive RSU was found to perform satisfactorily with threshold power of -90 dBm which is the standard power threshold requirement of the 802.11p standard for vehicular communication systems.

7.2 Future Work

The area of renewable energy powered communication networks is constantly evolving. An immediate future investigation involves developing a queueing model for optimum battery size to assess various reliability indices of a standalone wind powered RSU in motorway vehicular communications.

The advent of Internet of Things, smart information management on the fly, live video conferencing etc. translates to a demand for higher energy in vehicular communication systems and therefore opens the door for the development of various form of renewable energy with ease of deployment in an off-grid fashion.

The standalone RSUs explored in this thesis can be harnessed with appropriate routing protocols that facilitate intermittent placement of RSUs in a manner that minimises the number of functional RSUs for energy efficiency of the network.

Finally, further validation of the various simulation and analytic results obtained in this thesis should ultimately be undertaken through experiments.

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