ORGANIZED APPROACHES TO IMPROVE THE PERFORMANCE OF VEHICULAR NETWORKS

Thesis

Submitted in partial fulfillment of the requirements for the degree of
DOCTOR OF PHILOSOPHY

by

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DECLARATION

I hereby ***declare*** that the research Thesis entitled **Organized Approaches to Improve the Performance of Vehicular Networks** which is being submitted to the ***National Institute of Technology Karnataka, Surathkal*** in partial fulfillment of the requirement for the award of the Degree of ***Doctor of Philosophy*** in **Department of Electronics and Communication** is a ***bonafide report of the research work carried out by me***. The material contained in this research Thesis has not been submitted to any University or Institution for the award of any degree.

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CERTIFICATE

This is to certify that the Research Thesis entitled **Organized Approaches to Improve the Performance of Vehicular Networks**, submitted by **Patil Ashish Anandrao** (Register Number: 148032EC14FV12) as the record of the research work carried out by him, is accepted as the *Research Thesis submission* in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy**.

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Dedication

This thesis is dedicated to my parents

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Abstract

Vehicular Networking is an emerging technology defined with the main motive of avoiding on road accidents and providing safety and life critical applications to users in a well-organized manner. Vehicular ad hoc networks (VANETs) are main part of vehicular networks and this technology is becoming prominent in this era and it also aims at providing various entertainment applications in an orderly and efficient manner. In this thesis work, we present techniques to improve the performance of vehicular networks to transmit more data in lesser transmissions and reduce the channel congestion by controlling lower layers parameters. Index coding has proven its significance in reducing number of transmissions in wireless networks. This technique is used to reduce transmissions in vehicular networks, where multiple clients demand data from server and these demands are fulfilled by the server using index coding. Multiple files can be encoded into a single file of nearly same size using index coding. This transmission of multiple files in a single file reduce transmissions and eventually result in saving transmission bandwidth. Simulation results show that the proposed technique performs better over available techniques. Results are obtained for different initial repository contents of server and clients, to verify the protocol performance under various availability of required side information for index coding.

The idea of interconnecting everything in Internet of things (IoT) has evolved as a promising networking system and VANETs are one of the components of it. The aim is to connect every vehicle to every other vehicle for the purpose of improving users' quality of life. Decentralized Congestion Control (DCC) techniques are specified to reduce medium congestion and provide various safety applications. Decentralized congestion control techniques are presented which work by adapting transmit parameters combined with power. Message rate and data rate are the adapted parameters along with power control mechanism. These techniques are developed considering two-state active design proposed by ETSI and the performance is tested under real world scenario generated using SUMO. This adaptation of transmit parameters helps in maintaining congestion within specified limits proposed by the standard. There is increase and

decrease in message rate for message rate adaptation technique depending on available channel load and DCC state. This variation in message rate allows more channel utilization and the system is always maintained in active state.

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Abbreviations

Abbreviation	Expansion
ATIM	Ad hoc Traffic Indication Messages
AU	Application Unit
C2C-CC	Car 2 Car Communication Consortium
CAM	Cooperative Awareness Messages
CBR	Channel Busy Ratio
CCA	Clear Channel Assessment
CCH	Control Channel
CCHI	CCH Interval
CCW	Cooperative Collision Warning
CDMA	Code Division Multiple Access
CH	Cluster Head
CL	Channel Load
CPDRA	Combined Power and Data-Rate Adaptation
CPMRA	Combined Power and Message-Rate Adaptation
CSMA	Carrier Sense Multiple Access
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DCC	Decentralized Congestion Control
DSC	DCC Sensitivity Control
DSRC	Dedicated Short Range Communication
E2ED	End-to-End Delay
ETSI	European Telecommunications Standards Institute
Ex-OR	Exclusive OR
FCC	Federal Communication Commission
FCW	Forward Collision Warning
FDMA	Frequency Division Multiple Access
$GEMV^2$	Geometry-based Efficient propagation Model for V2V communication
GOS	Geographical Operations System
I-MERLIN	Index coding based Maximum Expected download over Random LINks
IRT	Inter Reception Time
ITS	Intelligent Transportation System
LOS	Line of Sight
MAC	Medium Access Control
MANET	Mobile Ad hoc Networks
MLME	MAC Layer Management Entity

Abbreviations

Abbreviation	Expansion
NLOS	Non-Line of Sight
NS-3	Network Simulator 3
OBU	On-Board Unit
PDR	Packet Delivery Ratio
PLE	Path Loss Exponent
PLME	Physical Layer Management Entity
QoS	Quality of Service
RSU	Road Side Units
SCH	Service Channel
SCHI	SCH Interval
SUMO	Simulation of Urban Mobility
TAC	Transmit Access Control
TDMA	Time Division Multiple Access
TDC	Transmit Data-rate Control
TPC	Transmit Power Control
TRC	Transmit Rate Control
U.S. DOT	United States Department of Transportation
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
V2X	Vehicle-to-X
VANET	Vehicular Ad-hoc Networks
VeMAC	Vehicular MAC
WAVE	Wireless Access in Vehicular Environment
WME	WAVE Management Entity
WSMP	WAVE Short Message Protocol

Chapter 1

INTRODUCTION

Intelligent transportation system (ITS) standards have defined various safety measures to minimize catastrophes caused due to surrounding environment and certain road conditions. Vehicular networks are defined to tackle above situations in well organized manner and improve users' comfort level. The communication between moving vehicles or between vehicles and road side units (RSUs) lead to formation of vehicular ad hoc networks (VANETs). They serve as one of the most important enabling technologies required to implement numerous safety and infotainment applications related to vehicles, vehicle traffic, drivers, passengers and pedestrians. It has two major types namely vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Intervehicle communication is attracting considerable attention from the research community and the automotive industry, where it is beneficial in providing intelligent transportation system (ITS) and also other services to drivers and passengers. Vehicles or nodes can be private or public. Private vehicles belong to individuals and those which are used for public transportation or services, come under public category. Many research communities and automotive industries are currently working in this area because of these attractive and challenging features of providing variety of communication services to end users. Dedicated short range communication (DSRC) is the medium for communication between these devices, hence each vehicle is equipped with DSRC device. IEEE 802.11p standard is adopted for physical and medium access control (MAC) layer functions and uses carrier sense multiple access with collision avoidance (CSMA/CA) for channel access Karagiannis et al. (2011), Moustafa and Zhang (2009).

The allocated spectrum for DSRC varies from region to region and are defined by the respective standardization committees of that region. Table 1.1 shows region wise DSRC spectrum allocations for U.S.A., Europe and Japan. In U.S.A., federal communication commission (FCC) have allocated the 75 MHz DSRC band for applications related to ITS and VANETs. This band is divided in to 7 channels as shown in Fig. 1.1. In Japan, DSRC bands for uplink frequency are 5835-5840 MHz and 5845-5850 MHz, and downlink frequency bands are 5790-5795 MHz and 5800-5805 MHz allocated by Association of Radio Industries and Businesses standard, ARIB STDT-55. It is expected that a typical WAVE device should use the Control Channel (CCH) and at least one Service Channel (SCH) during communication. The CCH (channel 178) is exclusively used to communicate safety and control information and SCH is used for non-safety or infotainment applications. The High power public safety (also known as high availability low latency (HALL)) and life critical safety channels (channel 172 and 184)are kept for future use Morgan (2010). The highest priority is given to CCH and it is expected that CCH should communicate with minimum latency.

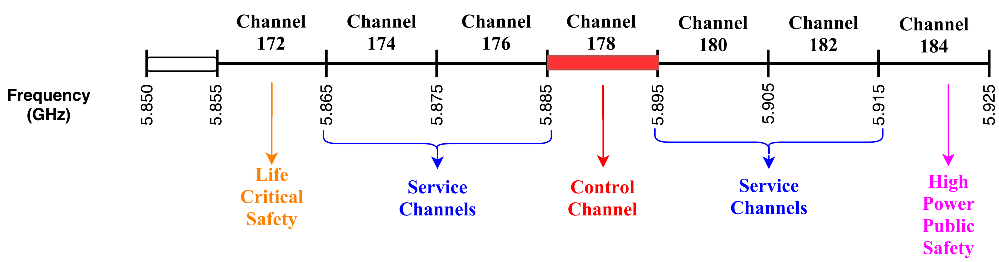


Figure 1.1: DSRC Channels

Wireless links are the major considerations in VANETs, since it highly influences the performance of the network. Wireless access in vehicular environment (WAVE) is the standard defined for higher layer operations by IEEE. IEEE 1609 family of standards for wireless access in vehicular environments (WAVE) is defined for higher layer operations. IEEE 1609 standard is divided for various applications as shown in Table 1.2. IEEE 1609.x standards are defined for operation at different layers of WAVE standards according to requirements of an application at respective layers. These WAVE and IEEE 802.11p standards are formed based on previous wireless standards by targeting requirements for vehicular networks. IEEE 1609.x includes 1609.1, 1609.2, 1609.3 and 1609.4, these standards are exclusively defined for applications related to vehicular networks. The medium access control (MAC) and multichannel operations under DSRC are covered by P1609.4 standard. It works by considering physical layer standards specified by IEEE 802.11p which is a modified version of IEEE 802.11a

Table 1.1: Region wise DSRC spectrum allocation

	U.S.A.	Europe	Japan
Contribution to Standardization	• IEEE 1609 protocol suite (Wireless Access for Vehicular Environments (WAVE)) • Car 2 Car Communication Consortium (C2C-CC)	• European Telecommunications Standards Institute (ETSI) • ITS and International Organization for Standardization (ISO) • Car 2 Car Communication Consortium (C2C-CC) • Continuous Air-interface Long and Medium range (CALM)	• Association of Radio Industries and Businesses (ARIB) • ISO CALM • ISO TC (Technical Committee) 204 committee
Frequency range	5850 - 5925 MHz	5795-5815 MHz currently in use 5855-5925 MHz allocated	*Uplink:* 5835 to 5840 & 5845 to 5850 MHz and *Downlink:* 5790 to 5795 & 5800 to 5805 MHz
Bandwidth	75 MHz	20 MHz in use	20 MHz

wireless standards. Networking and transport related operations such as routing, congestion, data dissemination, etc. are governed by P1609.3 standards by considering defined specifications. It also defines protocol stack managements information base and provides alternative for IPv6 as well. P1609.2 defines secure message formatting, data security and secure data exchange between vehicles. P1609.1 is specifically defined for WAVE resource manager, services required for WAVE resource management applications and message/data formats. It also provides architecture access to various applications. WAVE standard architecture is highly greeted and accepted by many VANET applications. Fig. 1.2 describes WAVE standards architecture IEEE (2010),

Table 1.2: IEEE 1609.x standards

WAVE standards	P1609.2	P1609.3	P1609.4	IEEE 802.11P
Services provided	• Security • Secure message formatting • Processing • Message exchange	• Networking services • Provides an alternative for IPv6 • Management information base for the protocol stack	• Multi-channel operation	• Modified version of IEEE 802.11a for Medium Access Control (MAC) operation of WAVE.

Moustafa and Zhang (2009).

The protocol architecture defined by IEEE for WAVE standard is shown in Fig. 1.3, it is mainly divided into two major planes namely, data plane and management plane. Data processing such as sorting data, adding or removing frame headers are addressed under data plane, and applications related to communication such as channel switching, synchronization etc. are focused under management plane. Since WAVE is specifically designed for vehicular networks, the WAVE Short Message Protocol (WSMP) under data plane imposes unique challenges on lower layers of WAVE stack. WSMP is unique component of DSRC and special services are required for WSMP packets such as particular transmit data rate or power. WAVE management entity (WME) under management layer is another unique component of WAVE standards and it defines different services to manage operations of various data plane layers. Along with quality of service (QoS) priorities, the transmission channel must be defined whenever data frames are scheduled. These QoS priorities must allow emergency and safety critical messages to be transmitted with minimum latency. Physical layer management entity (PLME) and MAC layer management entity (MLME) are defined for managing services for physical and MAC layer respectively.

Service providers and network operators in cooperation with government author-

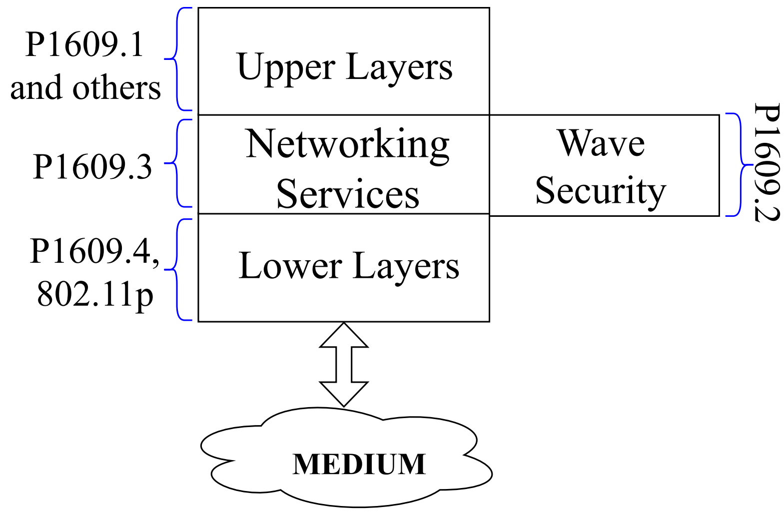


Figure 1.2: WAVE standards Architecture

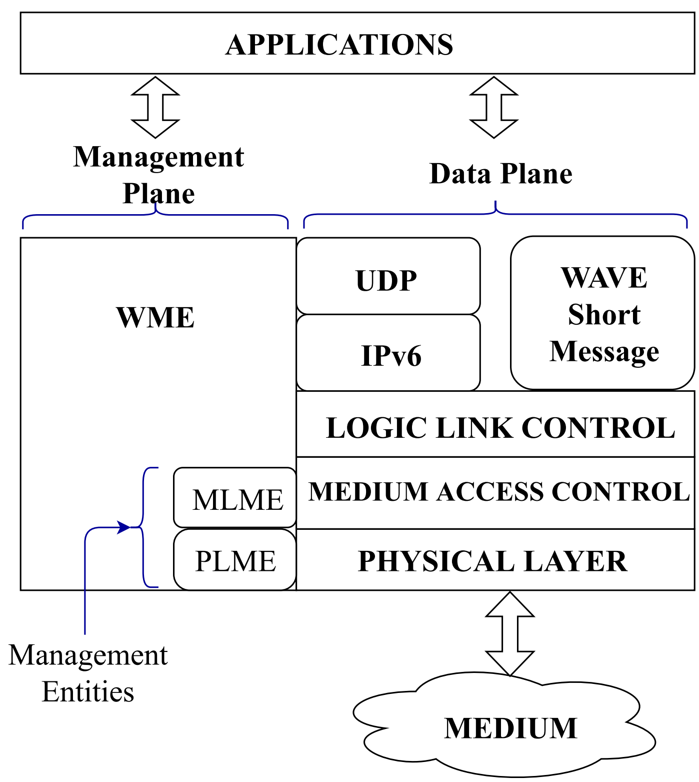


Figure 1.3: Protocol architecture for WAVE by IEEE

ities can deploy vehicular networks by considering safety and other application requirements. The network deployment can be of various types based on communication environment (for example, rural, highway and city). This can form different V2V

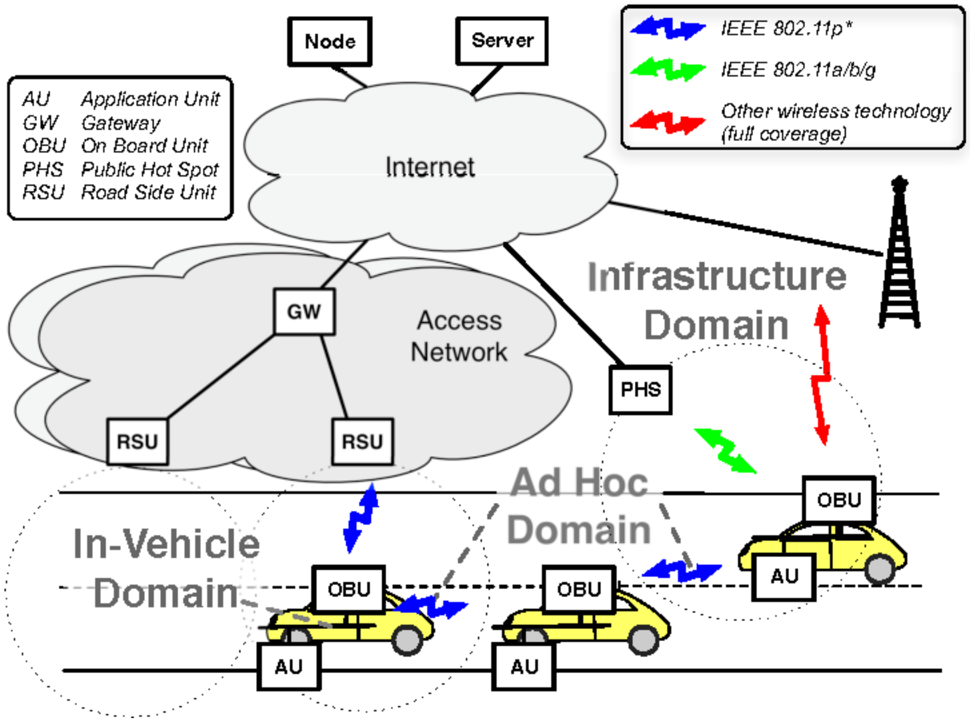


Figure 1.4: C2C-CC architecture [Liang et al. (2015)]

and V2I networks and communication should happen in a single hop or multiple hops depending on positions of source and destination vehicles. Fig. 1.4 shows reference architecture proposed by C2C-CC. Every vehicle is equipped with an on-board unit (OBU) and application units (AUs) where, number of AUs depend on type of applications. In general, an OBU is a mobile node and RSU is a static node of the ad hoc network. Direct or multi-hop communication is possible between RSUs and they can also be connected to Internet through gateways. In the absence of RSUs, OBUs can also get Internet access through hot spots (HSs) which are directly connected to the Internet. If RSUs and HSs are not present, the communication can happen using available cellular networks. Currently lot of research is going on in the field of 5G cellular network for VANETs Liang et al. (2015).

1.1 Characteristics of Vehicular Networks

The high mobility and continuous topology changes in VANETs enforce special characteristics and behavior, which distinguish them from other mobile networks. Following are some of the attractive unique features and challenges of VANETs compared with other wireless communication networks.

- *Immense transmission power available:* In conventional wireless networks, battery is the source of energy for deployed nodes, so the life of battery decides lifetime of network. In VANETs, this issue is not significant since the mobile node (vehicle) can be provided with continuous power from car batteries. This allows installation of high computing devices with each node for fast data processing which can improve computation speed of mobile nodes.

- *High mobility, but predictable :* In classic mobile ad hoc networks, nodes have random mobility and it is hard to predict node mobility during algorithm design. In vehicular networks, traffic rules have set speed limits for various lanes as well as information related to any specific region can be available from map-based technologies and positioning systems. Though the mobility is predictable, it is very high which makes operation environment of vehicular networks extremely dynamic. This happens because of fast changing topology due to very high mobility. Designing a protocol for this condition, where there is very short encounter duration between nodes is a challenging task.

- *Large scale Network :* The network size of conventional ad hoc networks is limited, but size of vehicular network varies from application to application. Sometimes, it may spread over entire road with large number of participants.

- *Divided into multiple segments :* As stated above, in large scale network there will be less reliability and data loss is more due to its dynamic nature. To overcome above issue, various isolated groups of vehicles can communicate with each other by forming clusters.

- *Connectivity and network topology :* The high mobility leads to shorter encounter time, causes continuous switching of links between nodes. This poses a dynamically changing topology for vehicular networks. The continuous position changes and high mobility gives short duration links and the connectivity is dependent on encounter time and transmission range of each node. Connectivity is also one of major concerns in vehicular networks.

1.2 Applications and Motivation

Mobile computing and wireless communication have experienced large improvements that led to the development of Intelligent Transportation Systems (ITS). In such systems the focus is on improving on-road safety and providing comfort applications.

1.2.1 Applications

In the United States, more than 42,000 people were killed and more than 2.8 million were injured in car accidents in year 2003 Morgan (2010). In India, more than 1.4 million people were killed and more than 5 million were injured in road accidents in year 2015 MoRTH (2015). This high number of fatalities and injuries cost huge amount in healthcare, more than any other type of injury or disease. Such issues make traffic safety a major concern to government agencies and automotive manufacturers, as well as researchers in related fields. Most of those accidents are preventable by implementing a comprehensive wireless communication mechanism for exchanging vital safety and emergency information between moving vehicles. Along with the prime aim of providing various safety applications to users, it is also supposed to provide non-safety applications such as transferring audio or video files, online video games, large data files transfer, providing in-vehicle Internet etc. These application can help users to get required information, entertainment, but at the same time it increases network overhead. Non-safety applications are mostly designed for passengers so that the journey can be delightful. The emergence of vehicular networking has encouraged researchers to study how such communications could be used to enhance driver safety. Vehicular networks are an exciting platform for developing new and useful applications Olariu and Weigle (2009).

Safety applications include information related to awareness of environment or any unsafe situation. It sends these critical messages to nearby vehicles or infrastructure after processing available safety data. Messages related to environment awareness are called periodic messages, whereas event driven messages are activated because of an unsafe driving situation. Traffic vigilance, information related to road hazards, co-operative collision warnings and post crash notifications are some of the safety applications. Non-safety applications include Internet access, downloading digital route maps, real time videos, electronic toll collection, active prediction parking assistance etc. Some of these non-safety applications help user in time utilization, tackling situations caused due to environments, saving vehicle fuel by choosing shortest or minimum traffic route.

This paragraph explains some of the implemented applications by various standards and committees. The message dispatcher (MD) is an interface that is added between different safety applications running on a vehicle and lower-layer protocols Robinson et al. (2006) . It eliminates redundant data and puts all the received information together in a single packet and send it to lower layers or broadcasts to nearby vehicles. Vehicles with single-vehicle-based technologies (e.g., parking sensors) are not able to share data with nearby vehicles, which limits their capabilities. Also, they do not function unless other vehicles are in direct line of sight. These issues have led to the development of other techniques to improve safety on the road. Extended emergency brake light (EEBL) application was an OEM-funded effort between BMW, Daimler Chrysler, Ford, GM, Nissan and Toyota. Cooperative intersection collision avoidance system (CICAS) was a four-year project sponsored by U.S. DOT Karagiannis et al. (2011). The main goal of CICAS is to prevent accidents between vehicles approaching or crossing intersections. CICAS works using two systems, one is an in-vehicle system and the other one is roadside system. The road tax payment is to be done electronically in many developing countries. Electronic toll collection system collects tolls from vehicles through OBUs at collection points. Once the type of vehicle is identified, OBU get notified and payment can be done. This communication process can happen through GOS and cellular network or wireless link at collection points.

1.2.2 Motivation

In this section, we state some of the characteristics and services which motivated us to choose this area for research. The on-road safety can be improved by providing various hazardous information to the network vehicle through single or multi hop communication. This information can be provided to vehicles outside the network by relaying RSUs or through cellular network. Assisting drivers in choosing path by providing information related to traffic jams and blocks, road accidents and other relevant information. Sometimes vehicles in other lane of highways can communicate the lane information or condition ahead to the vehicle traveling in opposite direction so that they can take some prior actions. This can be done by providing safe navigation for V2V and V2I communications in broader way for large-scale highly mobile applications. Provide entertainment, gaming and large data files during travel are some of the attractive applications of vehicular networks. Implementing these applications enforce lot of challenges on developers due to unique features of vehicular networks.

The communication between vehicles with high mobility, short encounter time, packet congestion, different transmission rates of vehicles and RSUs, duration of communication link, communicating with the vehicle traveling in opposite direction are some of the challenges in designing protocols or algorithms for vehicular networks. Broadcasting channel leads faster congestion, so controlling transmitted messages in the medium as well as considering required data to vehicles in these networks is one of the challenging tasks. The reduction in number of messages transmitted can improve channel utilization and can also save channel bandwidth. ITS have proposed different global and sustainable solutions for VANET, but the ad hoc nature impose various challenges in implementing those solutions. The amount of average traffic is growing every year, this increasing traffic lowers the accuracy of defined services. In the smart transportation system, vehicles make intelligent decisions in order to reduce fatalities, traffic congestion, avoid wastage of time and fuel which eventually improve user's quality of life.

1.3 Aim of this work and contribution

The on-road safety, driver assist, in-vehicle Internet system and infotainment applications are attracting researchers towards this field due to increase in usage of public and private transportation. VANETs support an exciting platform to various researchers for developing useful applications for the requirements of society. Many researchers have come up with various solutions and applications but the uncertain nature of vehicles and roads make vehicular networks a challenging platform for research. In medium or dense traffic scenarios broadcasting may lead to broadcast storm problems, reducing this along with saving channel bandwidth and controlling congestion in such scenarios is one of the challenging tasks. These scenarios also lead to the packet loss due to collisions and wastage of channel resources which may degrade the system performance. To achieve some of the challenges enforced by VANETs, following are the contributions of this thesis,

1) To develop a protocol which,

•*Reduces number of broadcasts and improves channel utilization in vehicular networks.*

•*Achieves higher download throughput and saves transmission bandwidth.*

Here, we apply a suitable encoding scheme to transfer more amount of data over the broadcast channel. More data is transmitted with minimum transmissions which save the transmission bandwidth at server.

2) To develop a decentralized congestion control mechanism by adapting various transmission parameters.

The frequent exchange of safety and awareness messages between vehicles can cause congestion in communication channel. Here, we propose congestion control mechanisms by applying suitable adaptation techniques based on available channel load. The congestion metrics should maintain limits specified by standard.

1.4 Organization

This thesis is organized as follows: In chapter 2, the background and related work in MAC and link layer protocol design and decentralized congestion control is surveyed in brief along with various challenges involved in their design. Chapter 3 presents design and analysis of I-MERLIN protocol proposed to reduce number of broadcasts and improve download throughput. In chapter 4, we present cross layered decentralized congestion control mechanisms to reduce channel congestion by controlling physical or link layer parameters based on available channel load. The contributions of this thesis are concluded in chapter 5 and indicated scope for future work in this area.

Chapter 2

BACKGROUND AND RELATED WORK

Enormous research have happened in the area of vehicular networks to provide various safety and non-safety services to drivers and passengers. In-spite of this, the industry demands more advancement and improvement in performance. In this chapter, we present a literature survey of the work carried out in this field. The work done at lower layers is presented in following sections which includes MAC and link layers and decentralized congestion control (DCC). The cross layered DCC techniques are proposed by ETSI to reduce channel congestion by controlling various parameters from lower layers (physical or link layer).

2.1 MAC Layer

In vehicular networks, the MAC protocol should cope with various issues discussed in previous chapter, but packet collision and hidden terminal Tobagi and Kleinrock (1975) are the main issues to focus on during the design of MAC layer protocols for vehicular networks. MAC protocols are usually classified into contention free and contention based protocols. In contention-based MAC protocols, nodes compete for channel access without any predefined schedule, whereas contention free MAC protocol tries to avoid collision by providing access to any one node at a given time.

To reduce collisions and provide access to nodes, several contention based and contention free MAC protocols are proposed in the literature based on frequency division multiple access (FDMA), code division multiple access (CDMA) and time division multiple access (TDMA) techniques. Most of the MAC protocols proposed for vehicular networks are based on TDMA techniques because of its flexible bandwidth resource allocation and rescheduling of time slots. In FDMA techniques, both the transmitter and receiver need to be frequency synchronized, which increases system complexity. In CDMA techniques, each node is assigned with a separate pseudo-noise (PN) sequence code. Length of a PN sequence code increases as number of nodes increases which make CDMA suitable for sparse traffic scenario in vehicular networks. We present survey of various MAC protocols proposed for vehicular networks in this section and summarize various challenges in designing the MAC protocols for vehicular networks. We divide existing MAC protocols in following groups: multichannel, cluster based, scheduling technique based, cooperative communication based MAC protocols. The protocols which fall in two or more groups defined above or which use different technique are classified into other MAC protocols.

2.1.1 Multichannel protocols

DSRC supports seven channels for safety and non-safety applications. Some of the protocols proposed in literature utilizes multiple channels for various applications and improvement of system throughput. The multichannel MAC protocols which are expected to utilize available bandwidth efficiently in high traffic scenarios, also focus on both safety and non-safety applications together.

The issues faced in use of both FDMA and CDMA technologies without any synchronization between mobile nodes for multichannel MAC protocol in mobile ad hoc networks (MANET) are reported in Wu et al. (2000). Dynamic utilization of multiple channels to improve the performance of ad hoc wireless networks is addressed in multi-channel MAC So and Vaidya (2004). The protocol enables multiple communications simultaneously in same region and different channels, also solves multichannel hidden terminal problem. A small window named ATIM (Ad hoc Traffic Indication Messages) at the start of each beacon interval is used for beacon messages. The ATIM window is a major overhead, since data packets cannot be exchanged between nodes even if they have previously exchanged ATIM packets. This protocol solves channel assignment and medium access together without the use of any clock synchronization.

A cluster based multichannel communication scheme integrating with contention free/contention based MAC protocols utilizes all the seven channels specified by DSRC. The traffic on CCH is consolidated to emergency safety messages only and other traffic is distributed over other SCHs Zhang et al. (2006). DSRC channels are categorized into inter-cluster control (ICC), inter-cluster data (ICD), cluster range control (CRC) and cluster range data (CRD) for a cluster based multichannel protocol (MMAC) proposed in Su and Zhang (2007). The above classification helps in efficient utilization of bandwidth over V2V networks through real time delivery of safety messages.

Multichannel token ring protocol (MCTRP) organizes vehicles autonomously into multiple rings operating on different SCHs through an adaptive ring coordination and channel scheduling Bi et al. (2009). The multi-channel structure of DSRC is related with intra-ring token in MCTRP to reduce contention between neighbouring vehicles. MCTRP gives quick delivery of emergency messages, improved network throughput and minimum channel access time for each node. A collision free and delay bounded transmission under various traffic conditions is achieved through adaptive broadcasting mechanism used in dedicated multi-channel MAC (DMMAC) protocol Lu et al. (2010). DMMAC uses hybrid channel access mechanism based on features of TDMA and CSMA/CA and also enhances protocol adaptability to different traffic conditions.

VeMAC a multichannel TDMA MAC protocol supports one-hop and multi-hop broadcast services on CCH, eliminates hidden terminal problem and reduces collisions due to node mobility Omar et al. (2013). The slots are assigned to nodes in SCHs in a centralized way and the protocol utilizes CCH and multiple SCHs during its operation. In VeMAC, nodes have equal opportunities to transmit their high priority application messages. Efficient broadcasts for high priority safety applications can be achieved using VeMAC, the effect of unbalanced traffic conditions and road-side-unit (RSU) existence on VeMAC are investigated in Omar et al. (2012). A modified version of VeMAC achieves higher throughput with an extra bit overhead in time slot field for collision information Kawakami and Kamakura (2015). For the protocol in Kawakami and Kamakura (2015), the possibility of collision is reduced, since communicating vehicles can take transmission decision based on the collision flag in time slot field, it also increases the time slot usage.

Minimum duration counter (MDC) Wang et al. (2013), a multichannel selection scheme emphasizes the fairness between SCHs using fairness index (FI) as well as balances the traffic of multichannel usage. The counter overflow problem as well as multichannel usage fairness are addressed using counter resetting schemes in Wang et al. (2013). A spectrum penetration based multichannel MAC (SPBM) protocol improves throughput of multichannel VANET MAC, which minimizes hidden terminal problem through cross channel data exchange. SPBM achieves non-safety message throughput, stability in safety message transmission, high channel utilization and adaptability to different traffic densities Jia et al. (2016).

A coordinated multichannel MAC (C-MAC) protocol Kim et al. (2016), provides contention free broadcasting of safety messages through RSUs which lowers collision probability and reduces required time for safety message transmission. SCH contention intervals are optimized for maximum throughput. As the collision probability and safety message transmission time are reduced, this saved energy leads RSUs to act as energy harvesters to VANET terminals. Here, RSUs are gateways for IoT devices in car. A multi-round elimination contention-based multichannel MAC (VEC-MAC) scheme decreases the collision probability in SCH, which also reduces collision rate and contention resolution time for service reservations Mao et al. (2017). VEC-MAC offers better system throughput on SCH in terms of the network load and the service packet length.

The *head of line* blocking raised due to large buffered packets can complicate queue management in multi-channel MAC protocol So and Vaidya (2004). This causes channel load balancing issue, as fixed traffic assumption leads to more pending packets in high density scenario. In MMAC, if the CCH is overloaded the safety message delivery is not guaranteed since only CCH is monitored by vehicle terminals and the safety message should have a dedicated CCH. Reserved channels stay unutilized due to change in network topology, this decreases the performance of DMMAC under high density scenarios. VeMAC cannot guarantee fairness in slot allocation when some nodes need more access to the channel to fulfill their requirements. Also, time slot wastage and packet errors caused due to the effects of various channel conditions are not considered in VeMAC. The efficient utilization of available bandwidth by utilizing all the DSRC channels is the main concern of multichannel MAC protocols. Table 2.1 summarizes multichannel protocols. Following are some challenges in designing a multichannel MAC protocol:

- Efficient use of all the channels by distributing load of one channel among all other channels.

- In dense traffic scenarios, using CCH only for emergency or high priority safety

Table 2.1: Multichannel MAC Protocols

Protocol	Scenario	Scalability	Issues addressed	Remark
Multichannel MAC So and Vaidya (2004)	-	Medium	Multichannel hidden terminal	Channel load balancing and ATIM window overhead issues are not solved
cluster based multichannel scheme Zhang et al. (2006)	Highway	Small	Channel busy rate	Overhead on CCH is more
MMAC Su and Zhang (2007)	Highway	Large	Bandwidth utilization	Reliability is not guaranteed when CCH is overloaded
DMMAC Lu et al. (2010)	Sparse, dense	Large	Safety message delivery, Adaptive broadcasting	Reserved channel stays unutilized if topology changes
VeMAC Omar et al. (2013)	Highway, city	Large	Hidden terminal, collisions due to mobility	Need an organized algorithm for time slot assignment to nodes
C-MAC Kim et al. (2016)	Highway with RSU	Large	Collision probability, Safety message transmission time	Works well in dense scenarios
VEC-MAC Mao et al. (2017)	Custom	Large	Packet delivery ratio, collision probability, contention resolution time for service reservations	Achieves better network throughput in terms of network load and the service packet length

applications and distributing remaining safety applications to other channels.

- Implementing efficient load balancing technique in high density scenarios.
- Achieving some of the QoS parameters such as, fairness by using multiple channels, throughput, probability of reception and reduced delivery delay of the system.

Multichannel MAC protocols show their significance in dense traffic scenarios because there will be more pending requests as well as safety concerns regarding on road vehicles.

2.1.2 Cluster based protocols

Cluster based schemes are efficient techniques to reduce data congestion and support various QoS metrics. Cluster based protocols are expected to deal with packet collisions, interference between clusters, slot allocation, reliability etc.

A self-Reorganizing slot allocation (SRSA) mechanism is proposed to reduce inter-cluster TDMA interference with less complex architecture and adaptive slot allocation mechanism Wu and Biswas (2005). A self-reorganizing cluster formation, autonomous cluster-head election and energy- efficient medium access control are the components responsible for successful operation of SRSA and to achieve better energy performance over CSMA based protocols. A cluster based multichannel communication scheme utilizes most of the DSRC channels Zhang et al. (2006). In Zhang et al. (2006), within a cluster most safety message traffic is exchanged in the TDMA and broadcast manner. IEEE 802.11 MAC is used among cluster head (CH) vehicles to guarantee safety message delivery. Protocol by Zhang et al. (2006), is developed based on three core protocols namely, cluster configuration protocol, intercluster communication protocol, intracluster coordination and communication protocol. Similarly, in Su and Zhang (2007), within a cluster most safety message traffic is exchanged in the TDMA and broadcast manner and IEEE 802.11 MAC is used among CH vehicles to guarantee safety message delivery. Analytical model with contention window size presented in Su and Zhang (2007), balances the trade-off between the delay of safety messages and successful delivery rate of safety messages supports different non real time traffics under various highway scenarios.

A Dynamic Backbone-Assisted MAC (DBAMAC), a distributed clustering algorithm for fast multi hop forwarding is defined through cross-layered design by Bononi and di Felice (2007). DBAMAC reduces collisions and contention delays by proactively refreshing the backbone of nodes. The cluster-based medium access control (CBMAC) protocol introduces QoS to the network and to minimize the effect of hidden terminals Gunter et al. (2007). The CBMAC forms stable clusters under low and medium traffic, also the data lost due to collisions is less. The problem of transmission delay caused due to frequent collisions is circumvented through a clustering based Multichannel MAC protocol (CMMP) and it also provides fast access to medium Kim et al. (2009).

Table 2.2: Cluster based MAC protocols

Protocol	Scenario	Scalability	Issues addressed	Remark
DBAMAC Bononi and di Felice (2007)	Highway	Large	Collisions, End to end delay, Number of broadcasts	Better performance is achieved through simulations
CBMAC Gunter et al. (2007)	City	Small	Cluster stability, hidden terminal problem	No clarity about behavior in dense traffic scenario
CMMP Kim et al. (2009)	Highway	Medium	Transmission delay, transmission ratio	Results are obtained at idle channel capacity of overheads
TC-MAC Almalag et al. (2012)	Highway	Large	Slot reservation, collisions in CCH	Results obtained for single cluster
CBT Sheu and Lin (2014)	Highway	Medium	Slot availability, inter-cluster and intra-cluster analysis	Protocol overhead depends on TDMA frame

The enhancement in data handle quantity is obtained by processing CCH and data channel separately. Improvement in total transmission ratio and reduction in MAC transmission delay is obtained in Kim et al. (2009), under specified overhead channel capacity.

A multiple control channels and self-organized vehicles clusters based multi-channel MAC protocol for V2V communication system has been developed to improve transportation safety. CDMA based Walsh codes are used to avoid hidden terminals and reduce intra-cluster end to end delay, also Vehicle Accident Avoidance Mechanism (VAAM) system is implemented in vehicles for verifying on road decisions Ding and Zeng (2009). TDMA cluster-based MAC (TC-MAC) algorithm for intra-cluster communication using TDMA slot reservation (light weight slot reservation) method decreases collisions, hidden terminal issue and packet drops in the channel Almalag et al. (2012). A cluster based TDMA (CBT) scheme Sheu and Lin (2014), uses transmit-and-listen scheme for electing coordinator and resolving collisions. In Sheu and Lin (2014), time slots acquisition is done using priority based traffic.

The performance of CBMAC under stressed conditions is not explored, also if packet doesn't reach the expected destination, it is counted as lost packet. The issues regarding cluster stability and data loss are not completely covered. The packet transmission in CMMP is less efficient and increase in neighbours can increase data handling quantity, which may cause the congestion. The safety message delivery depends completely on cluster structure in Ding and Zeng (2009). Inter-cluster communication is not considered in TCMAC, the performance is evaluated only based on parameters of single cluster. In CBT, the protocol overhead does not depend on number of nodes but it is dependent upon number of TDMA frames used. Clusters formed between vehicles travelling in same direction are more stable than the clusters formed by vehicles travelling in different directions. Cluster stability is one of main concerns in design of cluster based MAC protocols. Table 2.2 summarizes various cluster based protocols. Following are some of the challenges in designing cluster based protocols:

- Managing the data loss or packet drops when a cluster member loses connection with CH or enter into another cluster.
- To cope up with the topology due to vehicle speeds and directions.
- Reduction in the inter-cluster interference and intracluster collision.
- Dynamic slot assignment to vehicles of various clusters to avoid hidden terminal problem.
- Reduction in latency, collisions and transmission overheads in various traffic conditions according to priorities.
- Scalability of the protocol and slot reuse in contention free protocols.

2.1.3 Scheduling techniques based protocols

A 'PreemPrio-MAC' protocol with pulse based control mechanism realizes packet-level priority scheduling for emergency packets using preemptive priority services Peng and Cheng (2007). Pulses are used only in CCH and the CCH is monitored by all the listening nodes. PreemPrio minimizes hidden terminal problem and also guarantees lossless medium access for emergency packets. A self-configuring Vehicular Self Organizing MAC (VeSOMAC) Yu and Biswas (2007) designed for intervehicle data transfer through its in-band control mechanism for exchanging TDMA slot information during distributed MAC scheduling. Issue of frequent topology changes is addressed in VeSOMAC, it also offers better file transfer performance. A unified TDMA or weight-factor-based scheduling protocol proposed for V2I communications evaluated with respect to network throughput performance, fairness among vehicles and various accessing priorities Zhang et al. (2013). A collision free reservation (CFR) MAC provides collision free scheduling through a structured slot reservation based on the driving status and traffic flow of each vehicle Zou et al. (2014). CFR MAC addresses the issue of hidden terminal problem, reduces reservation delay and reduces transmission collisions.

A CSMA based adaptive and reliable multichannel TDMA (CS-TDMA) protocol considers the channel access scheduling and channel switching together Zhang et al. (2014). CS-TDMA provides reliable broadcasting by combining advantages of CSMA and TDMA, it also provides dynamic switching between CCH and SCH by adjusting dwelling ratio. A weight-factor based scheduler designed in Zhang et al. (2015), to improve network throughput in vehicular networks considers channel quality factor, speed factor and access category factor as design parameters. The reasonable and intelligent scheduling decisions are made based on information collected from communication links at RSU. A resource reuse for multiple V2V links is also developed to improve the performance of the scheduler in Zhang et al. (2015). A decentralized adaptive TDMA scheduling (DATS) strategy presented in Ke et al. (2013) has higher successful channel assignment ratio and lower time delay, it also reduces slot collision than ADHOC MAC Borgonovo et al. (2004) and VeMAC Omar et al. (2013). The ratio of time slots is adjusted dynamically according to node density during the node contention.

The round trip delay is more in VeSOMAC due to larger congestion windows which can also cause larger MAC queuing delays. The smaller reservation delay in CFR MAC helps vehicles to achieve steady state for efficient slot utilization. The reliability in CS-TDMA is achieved by varying CCH and SCH durations according to the traffic density, also channel switching and channel access is achieved together. The slot scheduling in DATS helps reducing the time slot conflict issue in VeMAC and ADHOCMAC which eventually reduces collisions. Since, the main motive of vehicular networks is on road safety, the scheduling based protocols should support priority scheduling to the safety and emergency messages. Table 2.3 summarizes different scheduling based protocols.

Table 2.3: Scheduling techniques based MAC protocols

Protocol	Scenario	Scalability	Issues addressed	Remark
PreemPrio-MAC Peng and Cheng (2007)	Highway	Large	Hidden terminal problem, lossless channel access	Supports multiple level of strict priority to emergency messages
VeSOMAC Yu and Biswas (2007)	Highway platoon	Large	Collision resolution, Packet drops	More round trip delay
CFR MAC Zou et al. (2014)	Highway	Large	Reservation time, hidden terminal problem, transmission collisions	More reliable and adaptive to reduce Reservation time and collisions
CS-TDMA Zhang et al. (2014)	Highway	Large	Dynamic channel switching and broadcast reliability	Access schemes and channel switching achieved together
DATS Ke et al. (2013)	Highway	Large	Fairness, reuse of resources	Resolves time slot conflict issue

Challenges in designing scheduling based MAC protocols include:

- Fairness with respect to communication channel quality, speed of vehicle and access category of the medium.
- Adaptive scheduling strategies according to traffic density in pending requests.
- Efficient slot reservation/assignment in minimum slot reservation time and collision reduction.

2.1.4 Cooperative communication based protocols

Some researchers have worked on cooperative communication based protocols for information transfer in V2V communication system. Latency, success probability and Cooperative Collision Warning (CCW) relevant applications are presented with respect to Forward Collision Warning (FCW) in ElBatt et al. (2006). FCW assumes that along with wireless communication device a vehicle has a localization device too. The proposed IRT latency metric in ElBatt et al. (2006), helps to capture successive packet collisions on latency caused by periodic broadcast based safety applications. A vehicular cooperative media access control (VC-MAC) protocol is developed for gateway downloading scenarios through cooperative communication Zhang et al. (2009). The unreliability of vehicular network channel has overcome in VC-MAC using spatial diversity and user diversity through cooperative relays which improves system throughput as well as cooperative information downloading.

Cooperative AdHoc MAC (CAH-MAC) protocol is developed for efficient and reliable packet delivery Bharati and Zhuang (2013). The throughput increment and reduction in time slot wastage due to dynamic VANET topology is achieved using CAH-MAC. Unreserved time slots are used by neighbouring nodes for retransmission of failed packets to reduce packet drop probability. A cooperative downloading algorithm, maxthroughput and min-delay cooperative downloading (MMCD) Ota et al. (2015), minimizes an average delivery delay of each user request while maximizing the amount of data packets downloaded from RSUs. MMCD reduces mean delivery delay while maintaining high downloading throughput in highway scenarios. Cooperative MAC proposed in Dai et al. (2016) makes good use of channel resources by improving system throughput and reducing time delay and packet loss rate. A vehicular cooperative TDMA (VC-TDMA) MAC protocol utilizes all time slots with dynamically choosing relay node and automatic cooperative communication Zhang and Zhu (2016).

The relevant positions of vehicle nodes are considered to be fixed during simulations performed for gateway broadcast scenario in VC-MAC. The relative mobility between nodes is not considered in CAH MAC which leads to static network topology for the considered time period. MMCD works well in sparse traffic scenario, but its download throughput degrades in dense traffic. So it is well suited for gateway downloading in highway scenarios where traffic congestion is less severe. Table 2.4 summarizes cooperative communication based protocols. Challenges in designing cooperative communication protocols include:

- Cooperative communication based protocols involve information transfer between vehicles, so the time required for information transfer between vehicles is main parameter to consider while designing.
- Develop an efficient buffer management technique in multi-hop communication scenario to overcome the problem of relay buffer overflow.
- Efficient broadcast scenarios to minimize latency and packet dropping and in-

crease packet delivery ratio.

- Develop slot utilization technique for contention free mechanisms to manage information transfer rate by considering relative mobility.
- To develop a drive-through internet system for in-vehicle internet access by considering a cooperative communication.

Table 2.4: Cooperative communication based MAC protocols

Protocol	Scenario	Scalability	Issues addressed	Remark
CCW, FCW El-Batt et al. (2006)	Highway	Medium	Packet loss, pre-packet latency	Degradation of performance at high density
VC-MAC Zhang et al. (2009)	Highway	Large	Reliability, spatial reusability	Results are obtained under relatively static topology
CAH-MAC Bharati and Zhuang (2013)	–	Large	Packet transmission delay, packet dropping rate	Relative mobility between nodes is not considered
MMCD Ota et al. (2015)	Highway	Large	Data loss, delivery delay	The throughput degrades for higher data size

2.1.5 Other MAC protocols

Various adaptive contention window approaches are presented in Stanica et al. (2011a), according to highly heterogeneous conditions. An adaptive physical carrier sense control is used to improve message reception probability in CSMA techniques Stanica et al. (2011b). Transmit and reserve (TAR), an ad-hoc MAC protocol used for detection and warning about critical situations is proposed in Khoufi et al. (2012). The efficiency and reliability of TDMA based MAC protocols is analysed in An et al. (2014), by considering average reservation delay, slot utility ratio and slot available duration as performance metrics.

A reliable R-ALOHA (RR-ALOHA) Borgonovo et al. (2002), guarantees reliable single hop communication, overcoming hidden terminals problem and also provides reserved channels of various bandwidths according to terminal needs. A dynamic TDMA mechanism implemented using ADHOC-MAC minimizes hidden terminal problem, also provides variable bandwidth, reliable channels which are needed for QoS delivery. A minimum number of relaying terminals are used to cover the network in ADHOC-MAC Borgonovo et al. (2004). The fixed frame length issue in ADHOC-MAC is overcome in Adaptive-ADHOC (AADHOC) MAC protocol by implementing a robust mechanism for adaptive frame length Miao et al. (2009).

Maximization of non-safety information is done by dynamically adjusting CCH interval (CCHI) and SCH interval (SCHI) to minimize the risks towards vehicular safety applications Wang and Hassan (2008). When traffic density is less, the safety interval can be used for non-safety application by optimizing the message generation rate of the safety applications. A similar work of dynamic channel switching leads to Vehicular Enhanced Multi-channel MAC protocol (VEMMAC) Dang et al. (2013) and the hybrid efficient and reliable MAC (HER-MAC) protocol Dang et al. (2014). The VEMMAC is more reliable for safety messages with higher throughput and adopts IEEE 1609.4 to allow communicating nodes to transmit non-safety messages during CCHI. The dynamic TDMA slot assignment technique in HER-MAC, utilizes SCH resources during CCHI for non-safety applications by allowing safety message transmission on CCH without collision within reserved time slot of each vehicle. More safety applications can't be transmitted because of limited availability of reserved slots.

A self-organized MAC protocol ensures efficiency and reliability of periodic beacon transmissions in VANETs using physical-layer network coding (VPNC-MAC) Ndih and Cherkaoui (2012). An overhead based relay assisted MAC protocol used symbol level network coding (SLNC) because of its lower error probability than the packet level network coding (PLNC) scheme Chen et al. (2012). This protocol achieves reduced packet delivery delay, improved throughput and successful transmission probability. VPNC-MAC needs to focus on time and frequency synchronization in highly dynamic scenarios. A self-organizing time division multiple access (STDMA) MAC Yu et al. (2013) with periodic broadcast packets work on the principle of automatic identification system (AIS) used in direct ad hoc communication between ships. STDMA always guarantees the real time channel access by reusing currently occupied slot within selection interval. Network coding based V2V safety messages dissemination algorithms are proposed in Achour et al. (2017). Network coding gain towars safety message dissemination is studied under various traffic densities. It is shown that network coding can be an effcient solution in overcoming the intermittent connectivity in sparse network. Vehicles are used as a backbone in interflow network coding technique used to design an efficient routing protocol for VANETs Wu et al. (2016). The reliable vehicle backbone is considered based on vehicle movement dynamics and their link quality. It reduces number of generated packets by 25% compared with conventional riuting protocol.

The reliability and performance of V2V system is modelled using 802.11a under DSRC assumptions. The effect of mobility on reliability and direct single hop broadcast networks is analysed in Ma et al. (2009). The performance and reliability requirements can be achieved simultaneously by adjusting back-off window size, carrier sensing and appropriate number of packet repetitions in Ma et al. (2009). An Adaptive Collision Free MAC (ACFM) Guo et al. (2012) protocol based on dynamic TDMA mechanism, provides more availability of slots ensuring the better channel utilization and fairness of channel access. ACFM works by shrinking slots assignment cycle frame by frame under light traffic. A risk-aware dynamic MAC (RMAC) protocol Guo et al. (2013) gives a reliable and practical stochastic model to predict average total number of potential collisions in a platoon of vehicles. R-MAC satisfy real-time and reliable delivery of messages by maintaining fairness between different kinds of messages in CCH. The large transmission delay is produced by R-MAC in overloaded traffic scenarios.

A collision free deterministic directional MAC is used for time-critical safety application in V2V communications to solve issues regarding time-bounded channel access delay and time-bounded message acknowledgement on highway scenario in Lann (2016). The half-concentrated and half-scattered self adaptive CSMA (HHSC) protocol Li et al. (2017) evaluates the impacts of node mobility on system throughput on highway scenario using Markov chain encountering model. A multi-round contention based protocol (VMR-MAC) Mao and Shen (2016), overcomes slot wastage problem by uniformly allocating slot resources to users through round by round contention. VMR-MAC gives better broadcast delay performance compared to VeMAC Omar et al. (2013). A spectrum database driven medium access control (SD-MAC) protocol Liu et al. (2017), achieves reliability and high system throughput for cognitive machine to machine (CM2M) in dense wireless applications.

The node mobility is not considered in ADHOC MAC, throughput reduction occurs when node mobility is applied. Also, the broadcast signalling channel needs frequent

Table 2.5: Other MAC protocols

Protocol	Scenario	Scalability	Issues addressed	Remark
ADHOCMAC Borgonovo et al. (2004)	–	–	Hidden terminal problem, reliable broadcasting	Broadcast signaling channel needs frequent periodic transmissions
VEMMAC Dang et al. (2013)	Sparse	Small	Average delay, safety message broadcasting	Bandwidth usage is more
HER-MAC Dang et al. (2014)	Traffic generated by simulator	Medium	Packet delivery ratio, slot reservation	During reserved emergency slots, a vehicle node cant send many safety messages
STDMA Yu et al. (2013)	Highway	Large	Probability of slot reuse, channel access	STDMA is sensitive to sensing range
VPNC-MAC Ndih and Cherkaoui (2012)	–	Medium	Packet reception rate, reliability	Network is underloaded, time and frequency synchronization need to focus more
ACFM Guo et al. (2012)	Highway	Large	Average delay, packet loss ratio	Protocol can be used in most of scenarios because of its adaptive slot adjustment technique
R-MAC Guo et al. (2013)	Highway	Large	Average delay, packet delivery rate, medium utilization	In overloaded traffic scenario transmission delay is large
VMR-MAC Mao and Shen (2016)	Sparse and dense traffic	Large	Channel utilization, slot wastage, broadcast delay	Event driven messages are not considered

periodic transmissions. There is more bandwidth usage in VEMMAC since the safety messages are broadcasted twice in CCHI and SCHI. In HER-MAC, The emergency slot reservation time increases as density increases, which eventually increase the delivery delay, also drops some of the safety messages. The slots are reused by farthest nodes within the sensing range in STDMA. This may cause packet collision and hidden terminals. The applied slot shrinkage and expansion procedure applied according to available traffic reduces delay in ACFM and also ensures fairness. In RMAC, under dense traffic scenario the message transmission delay is high but, a better fairness performance is achieved.

As vehicular networks possess dynamic characteristics, MAC protocols based on competition are more suitable than MAC protocols based on scheduling Han et al. (2012). The CSMA based protocols perform better over TDMA based protocols as vehicular density increases. The performance of these proposed protocols is Pareto optimal, still more focus is needed in designing MAC protocols for VANETs. These protocols are summarized in Table 2.5. Following are research areas needed to be focused while designing MAC layer protocols:

- The problem of hidden or exposed terminal should be minimized in dense traffic scenarios in order to make protocol more reliable with higher probability of reception.

- The TDMA based protocol should minimize collision problems by implementing dynamic slot assignment technique which could work in most of the traffic scenarios.

- The robust and scalable protocol implementation which will achieve higher throughput with lower access delay and guarantees timely delivery of safety and critical messages with priorities.

- The multichannel protocol which has fair channel access and error control techniques which has minimum adjacent channel interference.

- To cope up with data loss caused by frequent topology changes due to higher speeds of vehicles with some central coordinator.

- Implement a drive through internet system for invehicle internet access.

- Most of the protocols are designed for highway traffic, designing a protocol for various traffic conditions is one of the research challenges.

- Broadcast support with the broadcast storm control techniques, and implementation of efficient time or frequency synchronization techniques.

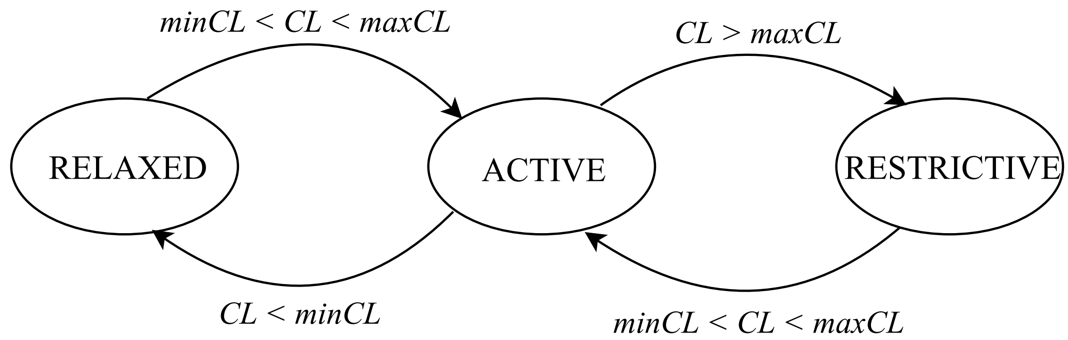


Figure 2.1: DCC_access state transition diagram ETSI (2011)

- The protocol should address bandwidth utilization in high density scenarios as well as resource allocation.

2.2 Decentralised congestion control (DCC)

The frequent exchange of safety messages in denser network causes congestion, the ETSI have specified various Decentralized Congestion Control (DCC) mechanisms to avoid congestion and improve fairness. DCC adapts transmission parameters based mechanisms that help to control channel load. Layer wise locations of components of cross layered DCC function are defined in ETSI (2011). It also defines access layer mechanisms namely, transmit rate control (TRC), transmit power control (TPC) and transmit data-rate control (TDC). Local channel congestion can be resolved by adapting the clear channel assessment under DCC sensitivity control (DSC). Transmit access control (TAC) and transmit queueing concept are defined to high priority packets with lesser restrictions. DCC is specified to be a mandatory component of an ITS-G5 station under ETSI. The DCC-Access, DCC-Net, DCC-Facility and DCC-Management are layers spanned by ITS-G5 station. The decentralized approach of DCC have three states namely relaxed, active and restrictive and the transition of states happen on the basis of available channel load with respect to defined threshold metrics. These states can be selected based on channel load (CL). The process happens to be in active state, if current CL is greater than minimum CL (minCL) and less than maximum CL (maxCL). When CL is less than minCL the process is considered to be in relaxed state, it enters in restrictive state once CL crosses maxCL. Fig. 2.1 shows state transition for DCC_access.

The cross layer DCC architecture for ITS-G5 and its functions and testable limits are provided in ETSI (2014). It focuses on DCC management functions and their interactions. The DCC gatekeeper is located at access layer to perform traffic shaping and on the basis of output from DCC algorithm, it restricts access to the particular channel. The cross layer concepts described in ETSI (2014) and various other relevant components such as PDR, Packet Inter-Reception time (PIR), Number of transmissions, channel busy ratio (CBR) and fairness are validated in ETSI (2015). The single message rate convergence and bounded stability are the stated key fundamentals while designing message rate based DCC algorithms.

The self-organized and decentralized approach for congestion control is performed because of high mobility and continuously changing network topology. Decentralized Utility-Based Packet Forwarding and Congestion Control (UBPFCC) is proposed in Wischhof and Rohling (2005), which uses utility function based on required application and encodes the utility information in each transmitted packet, which is transparent to all users in local area. UBPFCC is implemented over IEEE 802.11 MAC protocol and fairly allocates data rate to each user in the area through 'average utility value' of individual node. This allows nodes transmitting information with higher utility to utilize larger amount of available bandwidth for transmission. In high congestion scenarios, the packets having lower utility are dropped to increase the efficiency of information dissemination. A Vehicle-2-X (V2X) communication technology is proposed in Wedel et al. (2009), overcomes the negative impacts of traffic congestion. Here, vehicle routes are optimized on the basis of position of vehicle, current speed and direction received from neighbourhood vehicles. The proposed algorithm helps vehicles in the neighbourhood to change their path in case of high congestion and updates this information continuously. The penetration rate is used to evaluate the performance and higher V2X penetration rate makes more vehicles to use alternate routes to avoid congestion.

A distributed fair power adjustment for vehicular environments (D-FPAV), a transmit power control based mechanism is proposed to provide fairness and increase one hop probability of reception for periodic beacons and event driven messages Torrent-Moreno et al. (2009). D-FPAV maximizes the minimum power level over all assigned transmission power levels under the maximum beaconing load (MBL) constraint. Emergency message dissemination for vehicular environments (EMDV), a contention based fast and effective multihop data dissemination mechanism proposed in Torrent-

Moreno et al. (2009) satisfies active safety communication requirements. The channel load requirements ensured by D-FPAV is used in EMDV for successful operation and these two protocols together gains a synergy.

Additive increase multiplicative decrease data rate based congestion control techniques may not give fairness if there is no synchronization between nodes by 2-hop piggybacking mechanism. Periodically Updated Load Sensitive Adaptive Rate control (PULSAR), a transmission rate adaptation protocol is developed for safety applications as well as to satisfy awareness requirements Tielert et al. (2011). PULSAR uses a fixed interval called channel monitoring and decision interval for all nodes, in this interval it is assumed that all nodes are synchronized. The scheduled transmissions can be rescheduled in PULSAR and fairness can be achieved if convergence time is shorter. The Linear Massage Rate Integrated Control (LIMERIC), a linear adaptive congestion control algorithm is proposed in Bansal et al. (2013) for DSRC based safety communications. LIMERIC perfectly converges in noiseless environment providing significant improvement over convergence behaviour of limit cycle in binary control algorithms as well as fairness. The adaptation is provided with gain saturation to achieve robust convergence and stability in various scenarios. Environment-and Context-aware Combined Power and Rate control protocol (ECPR) proposed in Aygün et al. (2015) adapts transmit rate by controlling power based on environment effects and awareness distance. This combined power and rate control mechanism in ECPR presents feasibility analysis for environment and context aware scenarios. The frequency reuse can be possible because of transmit power adaptation in ECPR compared to rate-control algorithms.

The performance of DCC have been compared with some standard mechanisms in Autolitano et al. (2013). The instantaneous channel load value decides transition from less congested state to more congested state. It is shown that DCC performance can be improved by correlating it with application specific parameters to achieve desired outcomes. The impact of DCC mechanisms and their combined effect on the system performance is investigated in Vesco et al. (2013), counting PDR and channel access delay are the parameters to understand system behaviour. It is concluded that, DCC mechanisms are unable to reduce channel congestion and has low impact over system performance. The CCW based congestion control techniques for safety communication of periodic beacon broadcasts in decentralized vehicular environment are surveyed in Song and Lee (2013). There is more channel congestion in high density scenario due to more periodic beacon broadcasts. The need of V2V MAC protocol for safety application which adaptively controls congestion based on vehicle density and traffic condition in various environments is suggested in Song and Lee (2013).

A distributed network utility maximization (D-NUM) algorithm to avoid congestion caused by safety broadcast packets is proposed in Zhang and Valaee (2014). This distributed algorithm solves problem of safety benefit and expected delay in decentralized way. Sometimes, the equal safety benefits to all nodes can't be achieved through fairness, so D-NUM uses time slots for basic safety messages. The resource allocation provided by D-NUM prioritizes transmission from more safety-critical neighbours. A data rate based DCC (DR-DCC) framework is analysed in Math et al. (2015) for various traffic densities with the aim of providing safety applications along with congestion avoidance. DR-DCC works by varying data rate levels as per the current channel load and channel load is estimated by CBR. The beacon packets are transmitted at higher rates in DR-DCC and channel capacity is also improved. Data rate is the only parameter considered, the performance under other DCC parameters is not investigated and also there is no clarity about fairness. The increase in information penetration rate improves safety by increasing awareness of neighbourhood, but in dense traffic scenario it increases congestion. Transmit power control and intelligent adaptive broadcasting (TPA+IAB) a multi-metric algorithm is proposed in Frigau (2015) to overcome congestion and awareness control under two hop scenario. The algorithm works by taking into account the role of various performance parameters in decentralized awareness control (DAC) and DCC. TPA+IAB focuses mainly on controlling beacon generation rate and communication range and it is based on the PULSAR algorithm. A new metric fair bandwidth indicator (FBI) is introduced to measure the fairness index under influence of two hop scenario in DCC algorithm. TPA+IAB provides fairness as well as decreases transmit power in high density scenarios to avoid packet drops and limits interference as well as channel load. The combination of DCA and DCC will incur some overhead as compared with DCC algorithms, this overhead is not specified.

The robust and reliable multistate-active DCC mechanism is proposed in Gmez and Mecklenbruker (2016) to improve MAC-to-MAC delay, reliability and coverage range. It also improves DCC state stability by reducing transient states in system reliability. The reliability achieved is independent of traffic density as the protocol performance depends on carrier sensing threshold (CST) value. The decentralized Fair Adaptive Beaconing Rate for Intervehicular Communications (FABRIC) algorithm is proposed through gradient optimization techniques Egea-Lopez and Pavon-Mario (2016). This problem of controlling beaconing rate is approached by modelling it as a network utility maximization (NUM) problem under various static and dynamic traffic scenarios. FABRIC applies fairness notions while allocating beaconing rates to each vehicle and the fairness parameter α decides these rate allocations. In synchronous allocation case, the convergence of FABRIC to the optimum value happens quickly, whereas some oscillations exists in asynchronous case. The anti-flapping technique is also proposed to correct these oscillations. The fairness allocation in FABRIC depends only on α and the maximum beaconing rate is provided in almost all scenarios. In Khlmorgen et al. (2016), authors evaluated the performance of contention-based forwarding (CBF) for several protocol and shown that DCC-gatekeeper degrades performance of CBF by hampering its functionality. This DCC-gatekeeper based approach is enhanced to overcome above issue in proposed DCC Advanced. The messages are prioritized according to their traffic class in DCC-gatekeeper, which also controls transmission intervals. Once channel access is granted, in long queuing time scenarios, packets with exceeded queuing lifetime will be dropped and the one near to expiration time are forwarded.

Sometimes, vehicle with higher data rates get lower communication range and this makes some vehicles less visible in network which can cause unreliable and unsafe situations. The packet-count based decentralized data-rate congestion control algorithm (PDR-DCC) proposed in Math et al. (2017), enforces fairness and improves application reliability by homogeneous data rate selection. In terms of fairness, application reliability and awareness range, PDR-DCC outperforms DR-DCC and LIMERIC in congestion based networks. The protocol utilizes channel more efficiently and the fairness achieved by vehicle is independent of its time spent in the observing zone. It is also suggested that the reliability can be further improved for packet-count based approaches by adapting data-rate, message-rate, power, etc. Robust Overhearing Recovered Algorithm (RORA), an adaptive control algorithm is proposed in Kuhlmorgen et al. (2017) to evaluate the DCC-gatekeeper performance with packet prioritization focusing on interaction between queues. RORA improves the performance with respect to E2ED and reliability measured in terms of Vehicle Coverage Ratio (VCR). The priority queuing scheme of DCC-gatekeeper starves low priority packets beyond some vehicle density threshold. Weighted Fair Queuing (WFQ) can overcome this issue by assigning weighted fractions to queues based on the overall link capacity.

Table 2.6: DCC algorithms and protocols

Protocol	**Scenario**	**Scalability**	**DCC evaluation metrics**	**Remark**
UBPFCC Wischhof and Rohling (2005)	Highway	Medium	Packet drops, Fairness	May not work well in application specific scenarios
Vehicle-2-X Wedel et al. (2009)	City	Large	Traffic efficiency with respect to vehicle penetration rate	The effect of surrounding buildings is not considered
D-FPAV Torrent-Moreno et al. (2009)	Highway	Medium	Channel access time, probability of beacon reception	The fairness and reliability is achieved under realistic scenarios
PULSAR Tielert et al. (2011)	Highway	Medium	Fairness, CBR	Transmission range considered to be fixed
LIMERIC Bansal et al. (2013)	Generated by simulator	Large	Fairness	Can also works well with noisy and delayed input
D-NUM Zhang and Valaee (2014)	Highway	Medium	Resource allocation, packet received	Responds quickly to topology changes
DR-DCC Math et al. (2015)	Highway	Large	Inter-reception time, CBR	Fairness performance may degrade due to fixed power
TPA+IAB Frigau (2015)	City	Medium	Packet loss, fairness	Fairness get affected as density increases
FABRIC Egea-Lopez and Pavon-Mario (2016)	Highway, Bridge	Large	Beaconing rate, fairness, IRT	Quick resource allocation is achieved
RORA Kuhlmorgen et al. (2017)	Freeway	Medium	End-2-end delay, CBR	Priority queueing results in packet starvation at higher densities

A lot of research have happened at physical layer and channel modeling for vehicular networks. In this paragraph, we mention few of them which are related to DCC. OPRAM (OPportunistic-driven adaptive RAdio resource Management) technique developed for traffic safety applications works by adapting the information from proximity area near accident prone zone and different transmission parameters of the network. The traffic safety QoS requirements for different propagation channels even with correlated parameters can be compensated using OPRAM Sepulcre and Gozalvez (2009). The shadow fading model based on real measurements performed for urban and highway scenarios is developed over Nakagami-m fading using OPRAM Abbas et al. (2015). A highway data collected through stereoscopic aerial photography is used to implement in various simulators to develop obstacle based simulation models, considering vehicles as three-dimensional obstacles and to study their impact on various communication parameters Boban et al. (2011a). The implemented model in Boban et al. (2011a) works well for 2.4 GHz and 5.9 GHz and is computationally efficient, location independent and mostly compatible for highway scenario. This obstacle based model is successfully incorporated in NS-3 NS3 (2011). The vehicle density and a correlation model related parameters of log-normal model are tuned using matching mechanism proposed in Akhtar et al. (2015) and results show that the proposed method is a good match for obstacle-based model proposed in Boban et al. (2011a).

DCC algorithms and protocols are summarized in Table 2.6. The UBPFCC increases information dissemination efficiency but, the scheduling is not adaptive to applications. The effect of multi hop communication and surrounding buildings and scatterers is not considered in Vehicle-2-X, which may affect the performance. PULSAR is a reactive congestion control scheme used to achieve fairness through transmission rate adaptation but, the considered transmission range is uniform while performing simulations. LIMERIC uses realistic traffic and achieves fairness performance under noisy and delayed inputs as well as high density scenarios. It is one of the best algorithms to overcome congestion in challenging operating scenarios. D-NUM quickly responds to topology changes and provides fair resource allocation in safety critical environments.

DR-DCC has focused only on variable data rate, other parameters such as transmit power, carrier sensing threshold and message rate are kept fixed. This can affect the fairness and may lead to interference. The extra processing in TPA+IAB incurs some overhead which can affect the fairness at high densities although it has lesser packet loss. The rate adaptation in FABRIC reduces congestion in fewer steps with fair resource allocation to all nodes. The fairness allocation in FABRIC is controlled by single parameter but, this fairness notion may influence the safety in other scenarios. In PDR-DCC, T-window is defined as the reliability metric, where T is a tolerance time. T-window size is chosen based on the probability of requirements satisfaction of communication channel and this probability should be atleast 0.99. The priority queuing scheme used in RORA leads to starvation of low priority packets as density increases, also the message priorities are not considered.

Along with congestion control, DCC schemes should cope with some of the following challenges:

- Efficient information dissemination with minimum latency in high density scenarios.
- Reliable safety message transfer in any scenario.
- Adaptive and priority scheduling for safety messages as well as context aware scenarios.
- Interference cancellation schemes for carrier sensing in transmit power based schemes.
- Fair resource allocation to all nodes under topology changes and prevent data loss.

Chapter 3

IMPROVING DOWNLOAD THROUGHPUT AND SAVING TRANSMISSION BANDWIDTH

In this chapter, we present the technique to improve download throughput (or amount of data delivered by server) and saving of transmission bandwidth at server or RSU. The index coding technique is used to achieve the said goals, since multiple files can be transmitted in a single transmission using index coding technique.

3.1 Index Coding

The index coding is developed from the idea of Informed Source Coding-On-Demand (ISCOD) which uses broadcast channel to efficiently transmit non-identical data from a common server to multiple clients Birk and Kol (1998). The considerable bandwidth saving is achieved using ISCOD when many clients demand data in bulk. Index coding leads to favorable encoding scheme used to minimize the number of transmissions in an opportunistic network to satisfy all the client nodes. It is a special class of network coding with the basic idea of Zero-Error side information to encode a random variable with its jointly distributed another random variable over a noisy channel, where the receiver is having prior knowledge of jointly distributed random variable Witsenhausen (1976). The theoretical importance of index coding shows its usefulness for applications in intermittently connected ad-hoc networks. The index coding problem includes a server with set of information messages and set of receivers. A receiver

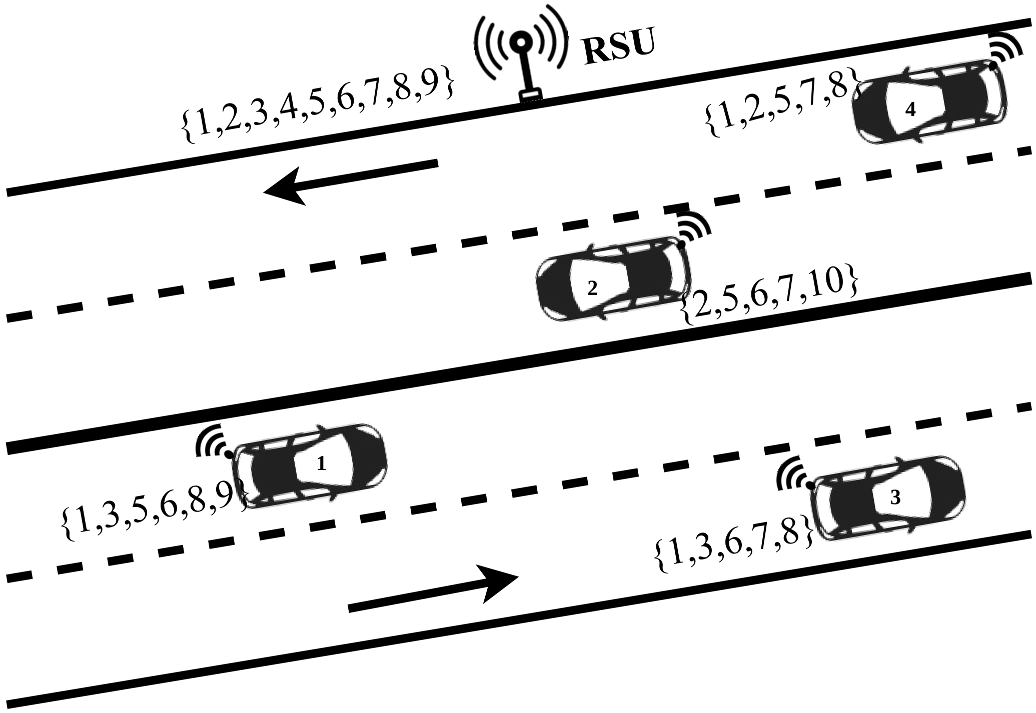


Figure 3.1: Index coding scenario for highway segment

needs to obtain a transmitted message from the server using side information. The objective of index coding is to find suitable encoding scheme that minimizes the number of transmissions required to satisfy demands of all receivers El Rouayheb et al. (2010).

To understand index coding, consider a simple road scenario with RSU acting as a server and vehicles are acting as mobile clients as shown in Fig. 3.1. Consider, RSU and travelling vehicles have some arbitrary set of files available with them from a set of 10 files. The file numbers which are available with RSU and each vehicle are shown in set beside them in the Fig. 3.1. Once RSU receives requests from all clients, RSU finds required files for each client and then apply possible index coding solution to reduce number of transmissions at server. Counting from left to right, client 1 needs files $\{2, 4, 7, 10\}$, client 2 needs files $\{1, 3, 4, 8, 9\}$, client 3 needs files $\{2, 4, 5, 9, 10\}$ and client 4 needs files $\{3, 4, 6, 9, 10\}$. Server checks for possible index coding solution before transmitting required files to each client. Since server is not having file 10 with it, it will not be able to fully satisfy those clients who need file 10. Client 1 has files $5, 6, 8$ and needs file 7, similarly, other clients need one file from files 5 to 8 and have remaining files. Server ex-ORs (index code) all these files together in a single file and transmits this one file by adding index coded file numbers in header as side information. The client who receives this index coded file can obtain their expected file by ex-ORing received file with required files available to it. In this scenario server transmits file $a = (5 \oplus 6 \oplus 7 \oplus 8)$, $b = (2 \oplus 3)$ and transmits files 1 and 4 separately. One more available index coding solution is $c = (1 \oplus 10)$, but server is not having file 10 with it, so it can't apply that solution. Clients can obtain such files through V2V communication if any of the client is having that file in its repository. Here, client 2 has file 10 with it, so other clients can get file 10 from client 2 through V2V communication.

In Challa and Cam (2007), the efficient utilization of bandwidth is achieved using spreading codes for a multicasting scenario in cellular and vehicular networks. The code utilization technique for users with poorest signal quality is proposed with adaptive data rate for V2I communication. Continuous change in multicast groups of users increases overhead with network load. An index coded scheme to reduce the message loss in VANETs is proposed in Hassanabadi et al. (2009), packets are encoded using index coding and feedback mechanism is used to propagate network information throughout the network. This scheme is having more average delay, since each node is taking index coding decision before transmission, which increases computational overhead on each node. The pliable index coding problem is used to satisfy all the clients using side information sets of each client by broadcasting coded message to them Brahma and Fragouli (2013). The problem is approximated and evaluated through simulations, it is also proposed that there exists a linear code despite server has incomplete side information. The index coding achieves bandwidth saving and reduction in transmissions when there are many clients requesting different data.

3.2 Reducing number of transmissions at server with improved data delivery

3.2.1 Proposed Model

MERLIN (Maximum Expected download over Random LINks) protocol is developed for optimizing downloads in vehicular networks over random encounter durations Bhargava et al. (2016). It maximizes the amount of data downloaded over an encounter lasting for random time. Here, clients may or may not make all the requests to server because of the limited encounter duration, client requests are organized by taking distribution of encounter duration into account. Clients request required missing files in the form of ranges in MERLIN, and the requests are made in descending order of the expectation of required ranges. In broadcast channel, if multiple clients request at different times, server may end up with transmitting same files multiple times and the waiting time for processing pending requests goes on increasing. We followed the optimization technique from MERLIN for client requests so that server can receive more information regarding required files to client. The index coding technique is applied at server to transmit multiple files in a single transmission which can eventually reduce number of transmissions at server as well as waiting time to process pending requests. As index coding is used to reduce transmissions and optimization technique used for making requests is followed from MERLIN, the proposed protocol is named as I-MERLIN (Index coding based MERLIN). To avoid pending of multiple requests at server, the server operation is made interrupt based. Server can interrupt its ongoing transmission and checks for new received requests so that it can apply new index coding solution depending on these received requests. This interrupt based server in I-MERLIN interrupts its transmission periodically to check for new client requests. The encounter time of client with server is modeled as a discrete random variable T with a known cumulative distribution function F_T. Server has an arbitrary subset of files available, denoted by vector S from a set of N files. Let there be M number of clients and the m^{th} client with different arbitrary subsets of available files be denoted as C_m, here m is the index of client in the network. Server vector $S = \{s_1, s_2, ., s_{Ns}\}$ has N_s files available and m^{th} client vector $C_m = \{c_{1m}, c_{2m}, ., c_{Ncm}\}$ with N_{cm} files available to it. $U_{Cm}(R_{bm})$ is the summed output of all required files to m^{th} client which has R_{bm} contiguous ranges. In our model, client requests required files to server in the form of ranges, once server receives request for required files it starts transmitting files available to it by applying suitable technique. Algorithms 1 and 2 present the processing taking place at server and client respectively. Required inputs for I-MERLIN are F_T, N_s, $(R_{b1}, R_{b2}, ...R_{bm})$ and the operation of I-MERLIN can be summarized below.

- The expectation of maximum data downloaded in R requests with F_T as exponential distribution is calculated by each client using eq. 3.1 Bhargava et al. (2016). Here, $D(R)$ is the amount of data downloaded in R requests, α and β

are constants used for problem parameters and λ is rate parameter.

$$E[D(R)] = \frac{e^{-\lambda\beta R}\left(1 - e^{-\lambda\alpha U(R)}\right)}{\lambda} \tag{3.1}$$

- Clients compute required ranges of files using equation 3.1 and request these files in the form of missing ranges to server in decreasing order of their expectation.

- If server listens from only one client in its listening interval, it directly starts transmitting requested files in the order requests are made. If server receives requests from multiple clients, it employs suitable index coding scheme and then transmit encoded files.

- Server interrupts its ongoing transmission after transmitting some specific amount of files/ranges or after some specified time period, and checks for new client requests so that it can apply index coding strategy for new received requests and also considering remaining files from previous transmission.

- Clients update their repository according to received files which it has requested, other clients whose requests are not processed can overhear the transmission medium and update their repository if they get a required file or able to decode the received file.

Algorithm 1 Processing at Server:

Require: F_T, N_s, $(R_{b1}, R_{b2}, ...R_{bm})$

1. Beacons no. of available files
2. After receiving requests from clients

if $M = 1$ **then**
  Transmit requested files in the order requests are received
else
  Transmit requested files using I-MERLIN
end if

3. Interrupt the ongoing transmission after specific interval, and check for new requests, then follow step 2.

Algorithm 2 Processing at Client:

1. Listen or overhear transmission from server
if Beacon received **then**
  2. Calculate expectation of required ranges from eq. 3.1
  and request them in descending order of their values
else
  if The received file is required file and/or decodable **then**
    update the repository with received file
  else
    discard file.
  end if
end if
Stop requesting if all the requested files are received and goes to listening state
else go to step 1

3.2.2 Experimental Setup

We used experimental scenario relevant to Fig. 3.2, with one static server and two mobile clients. Three Linux machines are used for performing experiments with one machine acting as server and other two acting as clients. Python-twisted is the simulation tool used to perform experiments, server machine runs python script to transmit data whereas clients use python script to receive data transmitted from server. Twisted is an open source event driven networking engine written in python. It is an asynchronous programming tool in which we can interleave multiple tasks in a single programming thread Fettig (2005), Peticolas (2009). This pipelining procedure of interleaving multiple tasks in a single programming thread utilizes unused space of blocking tasks in single threads. This event driven nature of twisted programming through callbacks, save execution time and waiting time is reduced.

The server machine runs server script to transmit files (coded or direct) and client machines having client script run to interact with server and receive required files. These experiments are performed by creating an ad hoc network through routers installed. We move client machines in and out of the server's transmission range at different times so that server decides index coding strategy when it receive requests from both clients. Fig. 3.3 shows satisfaction of both clients using MERLIN and I-MERLIN protocols. In MERLIN, the second client has to wait till server finishes its ongoing transmission to first client. In Fig. 3.3(b), we can see that, I-MERLIN server tries to satisfy both clients simultaneously by transmitting two files in a single

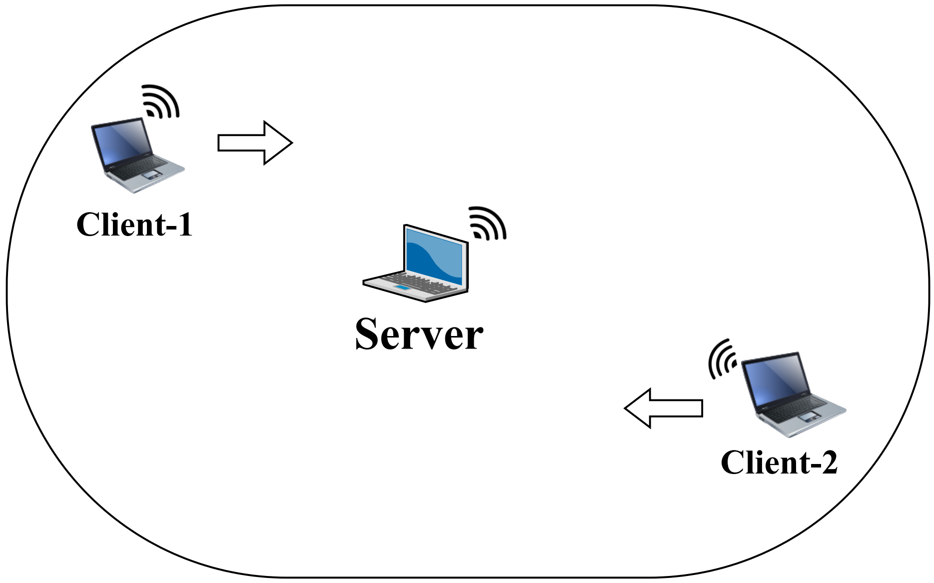
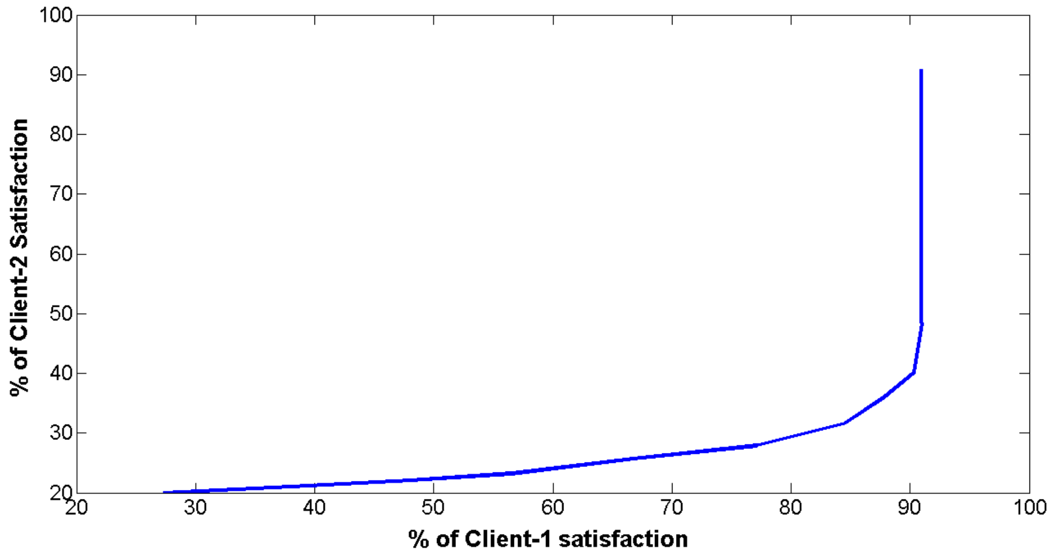


Figure 3.2: Scenario used for performing experiment

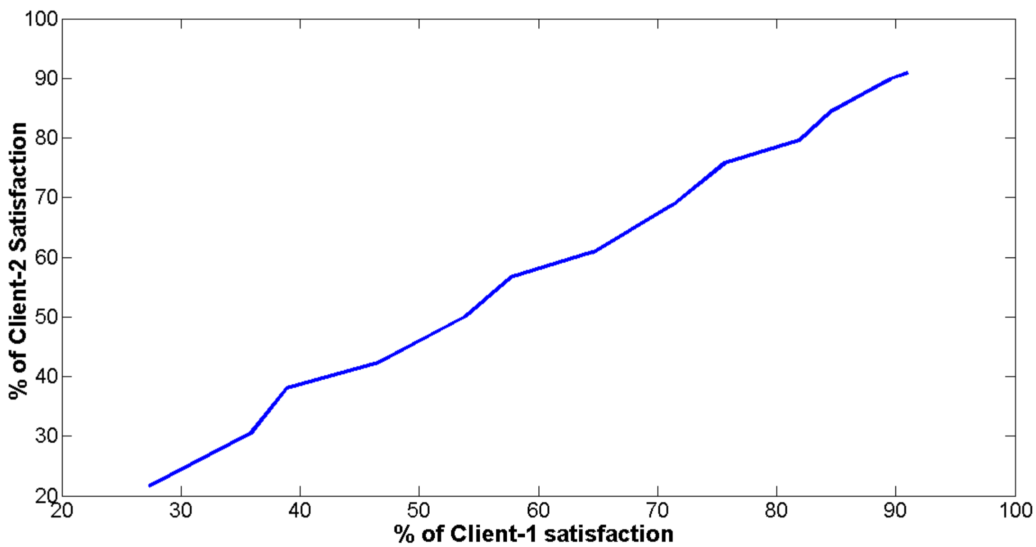
transmission using index coding. Non-linearities in Fig. 3.3(b) are because of the clients encountering with server at different time instants. If one client gets connected to server, the other has to wait till the server interrupts its ongoing transmission and checks for new client requests. Both the clients get fair utilization of data transmitted by I-MERLIN server with some added complexity at server. This reduces number of transmissions at server, which can lead in transmitting more data in minimum transmissions. Let, the data received for client i be d_{ri}, using I-MERLIN with two clients, and is given by equation 3.2. This received data gives the utility achieved by clients in receiving requested data from server. The equation 3.2 is valid for the case when clients receive all the requested files that are available with server.

$$d_{ri_m} = \frac{N_s}{N} \left\{ U_{C_m}(R_{bno}) + U_{C_m}(R_{bo}) + \pi_m U_{C_m}(R_{beno}) \right\} \tag{3.2}$$

Where, R_{bo}, R_{bno} are ranges of overlapping and non-overlapping files available with server which are requested by both clients respectively, π_m is the probability of occurrence of the client m having more number of non-overlapping files with it. R_{beno} are excess non-overlapping ranges which are available with one of the clients over other. Equation 3.2 is valid for the case where both clients receive all the files transmitted by server in these ranges, calculation of R_{bo}, R_{bno}, R_{beno} is done at server.



(a)



(b)

Figure 3.3: Client satisfaction using (a) MERLIN, (b) I-MERLIN

3.2.3 Results and Discussion

We use around 100 data files containing different data of various sizes (size of file depends on the content in that file). Files available to server and client are varied for each experiment performed and by default are set to 90% and 20% respectively. These values are chosen so that clients can have some side information and server should have most of the requested files. The experiment is performed for one static server and two mobile clients. Fig. 3.4 shows the satisfaction of two clients using MERLIN and I-MERLIN. It is observed that, in MERLIN the second client has to wait till server finishes transmission to first client. This technique allows one client to receive data and other client has to wait till server responds. The server has to transmit more amount of data in this technique, since it doesn't know about the required data for other client and it doesn't apply any encoding technique. In I-MERLIN, after getting requests from both the clients, server apply index coding strategy for received ranges from both clients so that both clients get satisfied fairly. If only one client gets connected and started receiving files from server, the interrupt based operation of I-MERLIN server periodically checks for new available clients, applies index coding and transmits index coded files. I-MERLIN satisfies both clients simultaneously with minimum transmissions which eventually reduces number of requests from clients who have updated their repository with received files. The second client in MERLIN has to wait till server responds to its requests, it increases number of transmissions of MERLIN server in high traffic scenarios or when there are more number of vehicles.

Fig. 3.5 and Fig. 3.6 show total requests made by both clients using MERLIN and I-MERLIN, these results are plotted for server with 40% and 90% files availabilities respectively. It is observed that, total number of requests made by both clients in I-MERLIN are less as compared to requests made by clients in MERLIN, due to index coding and interrupt based operation. Clients update their repository every time they receive requested file from server which eventually reduce requests from clients during next encounter. I-MERLIN protocol performs better by reducing total number of requests made and simultaneously satisfying both clients. Index coding approach performs effectively when there is high availability of files with server. The error bars show that, the variation in number of requests made for certain client availability is less in I-MERLIN than MERLIN. I-MERLIN is superior over MERLIN when it comes to simultaneous satisfaction of multiple clients in minimum number of requests. The performance achieved using I-MERLIN is at the cost of increased complexity, which is not a main concern in vehicular communication network, currently. Since, high availability of battery power from vehicles allow to install high computing device on vehicles Moustafa and Zhang (2009).

When we were moving clients in and out of the transmission range of server,

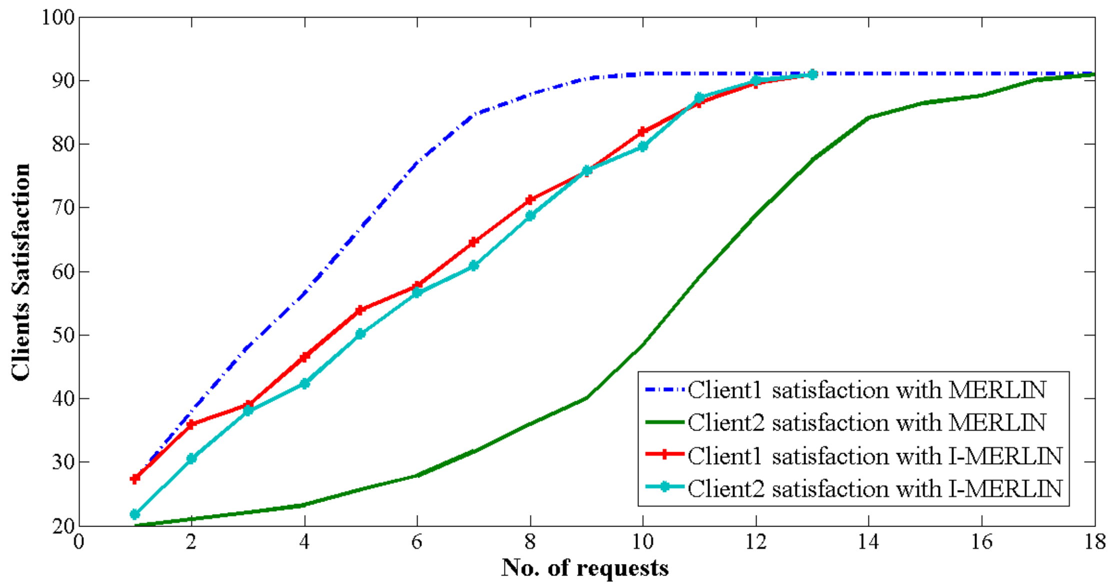


Figure 3.4: Satisfaction of two clients using MERLIN and I-MERLIN

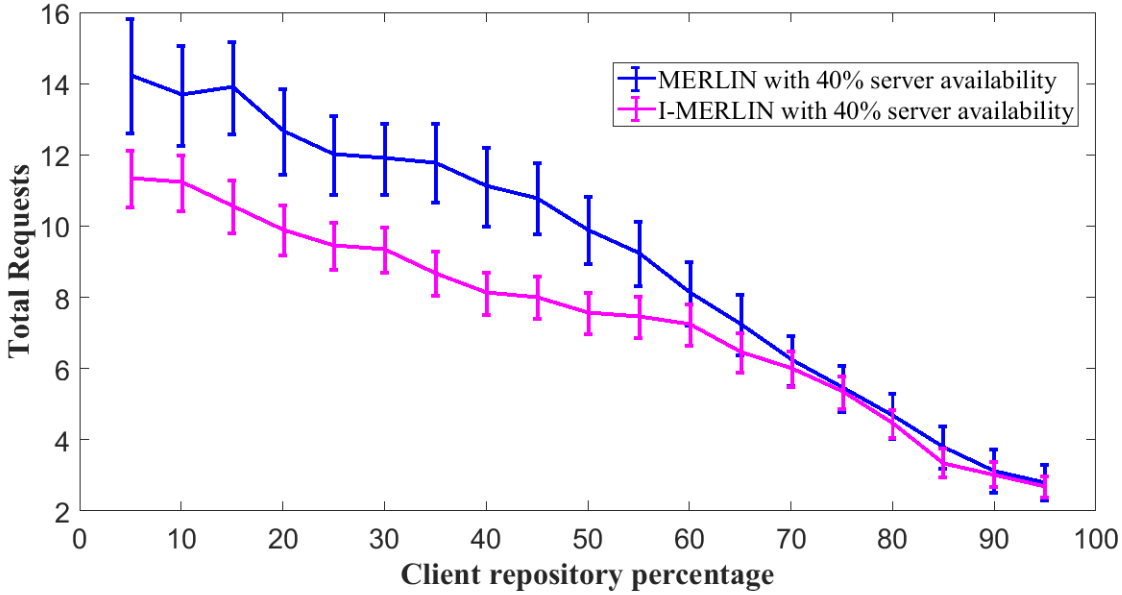


Figure 3.5: Comparison of total requests made in MERLIN and I-MERLIN with 40% of server availability

the client was not getting automatically connected to server when it comes again in transmission range. Client re-connection is one of the unsolved issues in twisted, so we used a manual reconnect procedure for clients to connect with server when it looses connection with server. Once client is out of server's communication range, the

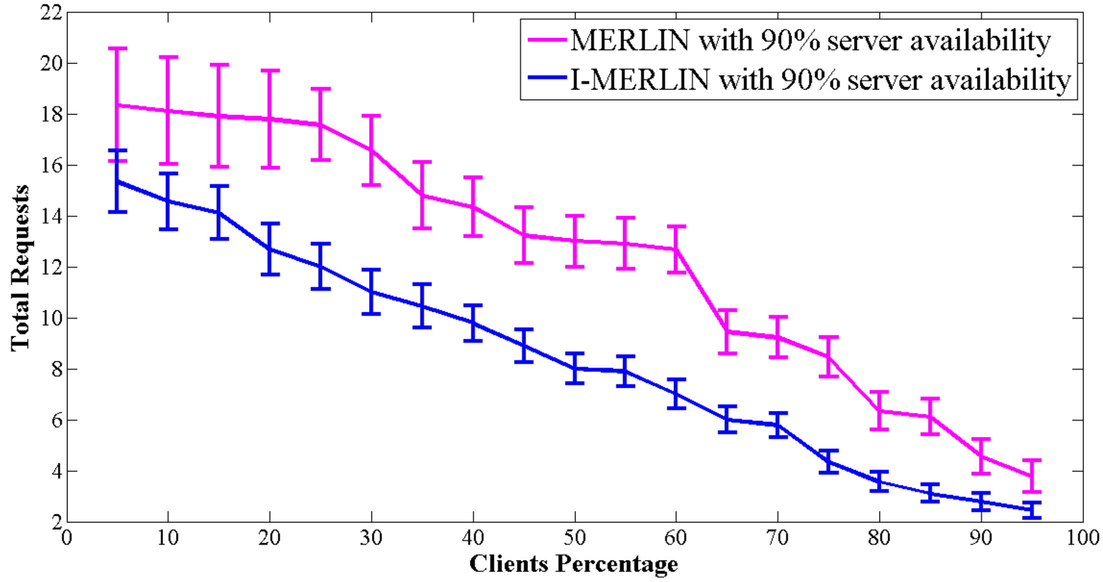


Figure 3.6: Comparison of total requests made in MERLIN and I-MERLIN with 90% of server availability

current client script was restarted with updated repository content before entering into the servers' communication range. This manual reconnect procedure can lead to improper readings when there are more number of clients in the network, hence we limited number of clients to two. This proposed design is extended to any number of clients in the network and server can take index coding decision for the available number of clients within the encounter time of clients. In next section, we propose the extended version of I-MERLIN protocol and it is implemented in Matlab relying on realistic assumptions made in literature.

3.3 Saving transmission bandwidth and increasing data delivery using I-MERLIN

In previous section, we propose I-MERLIN protocol to reduce the number of transmissions at server and to satisfy multiple clients requests with minimum transmissions. The experimental scenario considered is very small due to fundamental bug in tool used. Increasing number of clients in such scenarios is not feasible. In this section, we give generalized design and analysis of I-MERLIN protocol.

3.3.1 Model and Notations

We consider a highway scenario where multiple vehicles with different data repositories try to download data from server by providing the available content in their repository as the side information. Each vehicle is equipped with the storage device along with the DSRC radio. The arrival of vehicles is considered as Poisson process having randomly distributed vehicles with inter-vehicular distance in each lane to be exponentially distributed. The probability of occurrence of m vehicles along a given length of road segment d is given by equation 3.3. This equation gives the probability with which M number of vehicles are present in the given length of road segment Bharati and Zhuang (2012).

$$p(M,d) = \frac{(\rho d)^M e^{-\rho d}}{M!} \tag{3.3}$$

Here, ρ is the total vehicle density of all lanes measured as vehicles per unit length and it is given as, $\rho = \sum_{l=1}^{L} \rho_l$. Where, L denotes total number of lanes present and ρ_l is the vehicle density for lane l in vehicles per unit length.

As shown in Fig. 3.7, access points or RSUs are acting as server and mobile vehicles requesting data are considered as clients or nodes. RSU is having most of the data requested by vehicle nodes, and it takes the index coding decision for transmitting requested data to clients. There are M number of vehicles and they contend to occupy the channel access. Server and clients have data in the form of files, server has N_s files available with it from N total files. The content in repository of each vehicle is denoted as C_m, where $m \in \{0, 1, ..., M\}$. Here, C_m is an array representing data available with vehicle m and let m^{th} vehicle has N_{C_m} files available in its repository. Clients request required files to server in the form of missing file ranges. We denote $U_{Cm}(R_{bm})$ as the summed output of all required files to m^{th} client which has R_{bm} contiguous ranges Bhargava et al. (2016). When all clients requesting different files and server has the side information regarding the available repository of each client, the index coding technique can save bandwidth as well as number of transmissions. When server receives requests from each client, it has to transmit data $(S\backslash C_1), (S\backslash C_2), ...(S\backslash C_M)$ to clients $1, 2, ..., M$ respectively. Where, S stands for content available in the repository of server.

The index coding technique cannot be applied if all clients request similar data i.e., if common or overlapping data content is requested by all clients then it is broadcasted

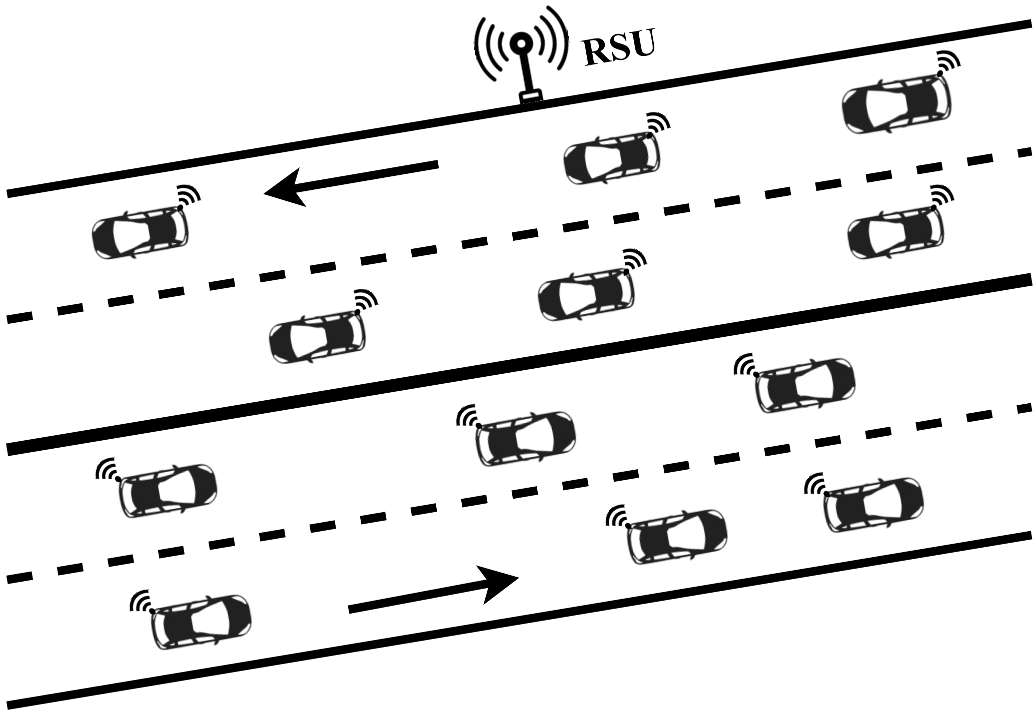


Figure 3.7: Index coding scenario for highway segment

as it is without applying index coding. Let Ov_m be the overlapping data between m number of clients, $m \in \{0, 1, ..., M\}$ and it can be obtained from equation (3.4). Server finds non-overlapping data by excluding this Ov_m from each requesting client's repository. $C_{Nov_1}, C_{Nov_2}, ..., C_{Nov_m}$ are the non-overlapping content required to each client and obtained from equation 3.5. The process of index coding (Ex-ORing) non-overlapping data requested by clients, encapsulates all data in a single data file of nearly same size of data file requested by individual client. In other words, server needs to transmit the file that can be obtained by ex-ORing (index coding) all other files together. This transmits multiple requested data files by client in a single file and saves the transmission of all other files at server. The received encoded data file is decoded by each client by Ex-ORing it with the required available files in repository. To do this, client needs the side information used to index code the received file.

$$Ov_m = [(S \backslash C_1) \cap (S \backslash C_2) \cap ... \cap (S \backslash C_m)] \tag{3.4}$$

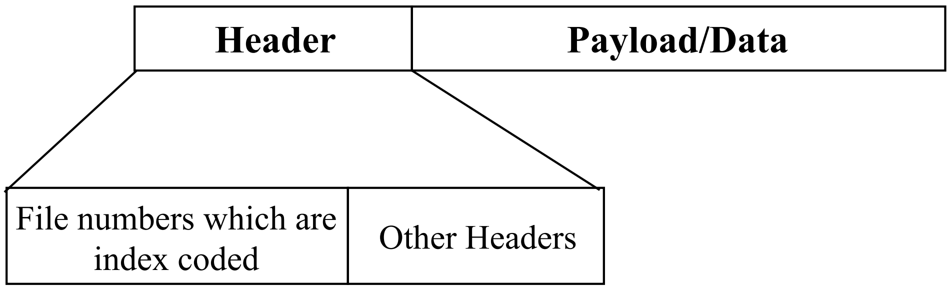


Figure 3.8: Packet format

$$
\begin{aligned}
C_{Nov_1} &= (S \backslash C_1) \backslash Ov_m \\
C_{Nov_2} &= (S \backslash C_2) \backslash Ov_m \\
C_{Nov_m} &= (S \backslash C_m) \backslash Ov_m
\end{aligned}
\tag{3.5}
$$

The received index coded file is easily decoded once the side information used to encode the file is provided to each client. This side information is provided by the server to all clients by adding little extra overhead in regular packet header. We use packet header to provide this side information, the details of data files used to index code the transmitted file are added in packet header as shown in Fig. 3.8. The index coded data field in header contains file numbers which are index coded to encode the transmitted file. This data can be helpful to each client in decoding received file by ex-ORing it with the files required to decode the file. Communication happens through broadcasting, so any client can receive the data transmitted by server. The client decides about decoding of file by just checking its own repository and received file header, it updates the repository with the received file, if it is required one.

3.3.2 Design and Analysis

We consider the highway scenario where vehicles in the transmission range of RSU request data in the form of missing file ranges. Only SCH intervals are used for non-safety message transmission and CCH interval is kept for event driven safety applications. The carrier sense multiple access with collision avoidance (CSMA/CA) a contention based channel access mechanism is used. Nodes contend to access the medium and request the required data from RSU once they get channel access. When RSU receives requests from various clients, it applies index coding to the available data by finding appropriate side information and then transmits the encoded data to the medium.

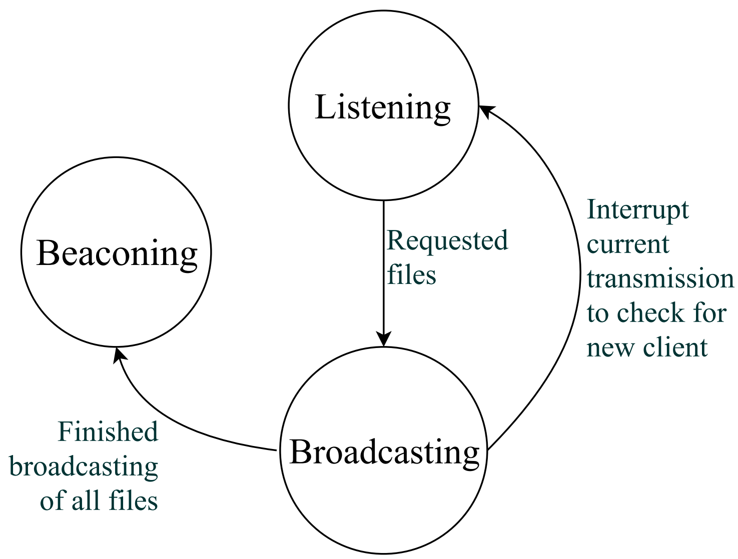
When two clients are requesting, server finds non-overlapping files between clients and then it checks for available files in repository of other client and takes index coding decision. From C_{Nov_1} and C_{Nov_2}, C_{2IF_1} and C_{2IF_2} can be found using equation 3.6. C_{2IF_1} and C_{2IF_2} represent the file numbers in clients 1 and 2 respectively, which can be index coded for group of two clients and are completely decodable at the receiver (in this case, either client 1 or client 2 are considered receivers by server). Total number of files that can be index coded between two clients are $min\,\{|C_{2IF_1}|, |C_{2IF_2}|\}$. Similarly, total number of files that can be index coded between three clients are $min\,\{|C_{3IF_1}|, |C_{3IF_2}|, |C_{3IF_3}|\}$. Where, C_{3IF_1}, C_{3IF_2} and C_{3IF_3} can be calculated using 3.7. Equation 3.8 gives files requested by each client, which can be index coded for groups of $'M'$ clients and are completely decodable. After applying index coding for three clients, server will check for possible index coding combinations between groups of two clients for remaining non-overlapping files.

$$\begin{aligned} C_{2IF_1} &= C_{Nov_1} \cap C_2 \\ C_{2IF_2} &= C_{Nov_2} \cap C_1 \end{aligned} \tag{3.6}$$

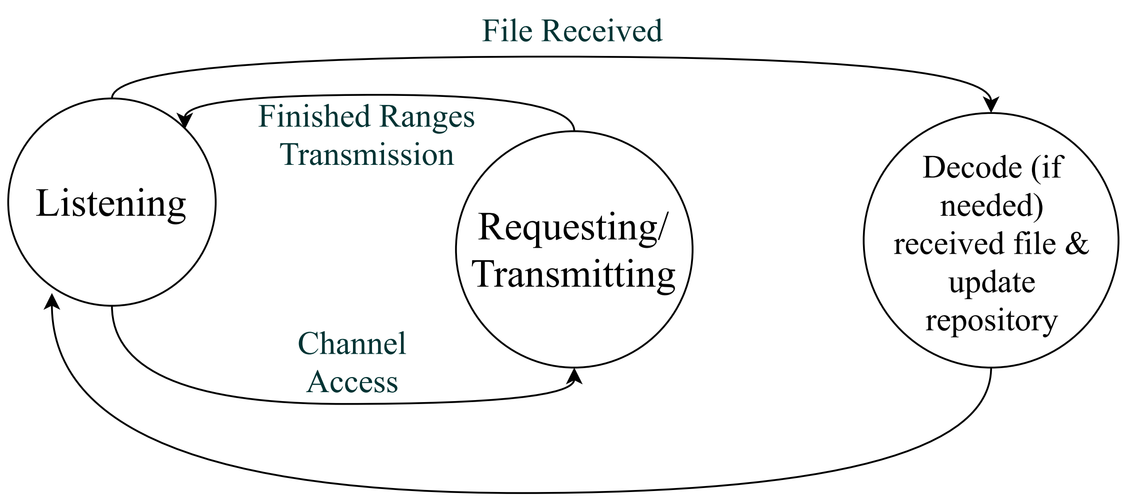
$$\begin{aligned} C_{3IF_1} &= C_{Nov_1} \cap C_2 \cap C_3 \\ C_{3IF_2} &= C_{Nov_2} \cap C_1 \cap C_3 \\ C_{3IF_3} &= C_{Nov_3} \cap C_1 \cap C_2 \end{aligned} \tag{3.7}$$

$$\begin{aligned} C_{MIF_1} &= C_{Nov_1} \cap C_2 \cap C_3 \cap .... \cap C_m \\ C_{MIF_2} &= C_{Nov_2} \cap C_1 \cap C_3 \cap .... \cap C_m \\ &..... \\ C_{MIF_m} &= C_{Nov_m} \cap C_1 \cap C_2 \cap .... \cap C_{m-1} \end{aligned} \tag{3.8}$$

As number of clients go on increasing, the process of checking index coding solution becomes more and more complex, since finding various possible index coding combinations between m clients increases complexity to $O(2^m)$. Server has to check all received requests from clients in the medium and find the suitable index coding solution between groups of m clients. This process continues till server checks for all possible index coding combinations between various groups of clients. If m goes on increasing, the number of possible groups for index coding goes on increasing which eventually increases complexity. In order to reduce complexity, we have divided total clients in the combination to groups of three and two clients. These computations happen at stationary RSU which always has extra high speed computational device installed for better performance. These groups of three and two clients are formed randomly at RSU, so that received requests can be processed faster. Let g_3 and g_2 denote total groups of three and two clients respectively, which reduces the complexity to $O(2^2 g_2 + 2^3 g_3) = O(4g_2 + 8g_3)$.



(a) Server



(b) Client

Figure 3.9: State transition diagrams

The state transition diagrams of server and client are shown in Fig. 3.9. Fig. 3.9(a)

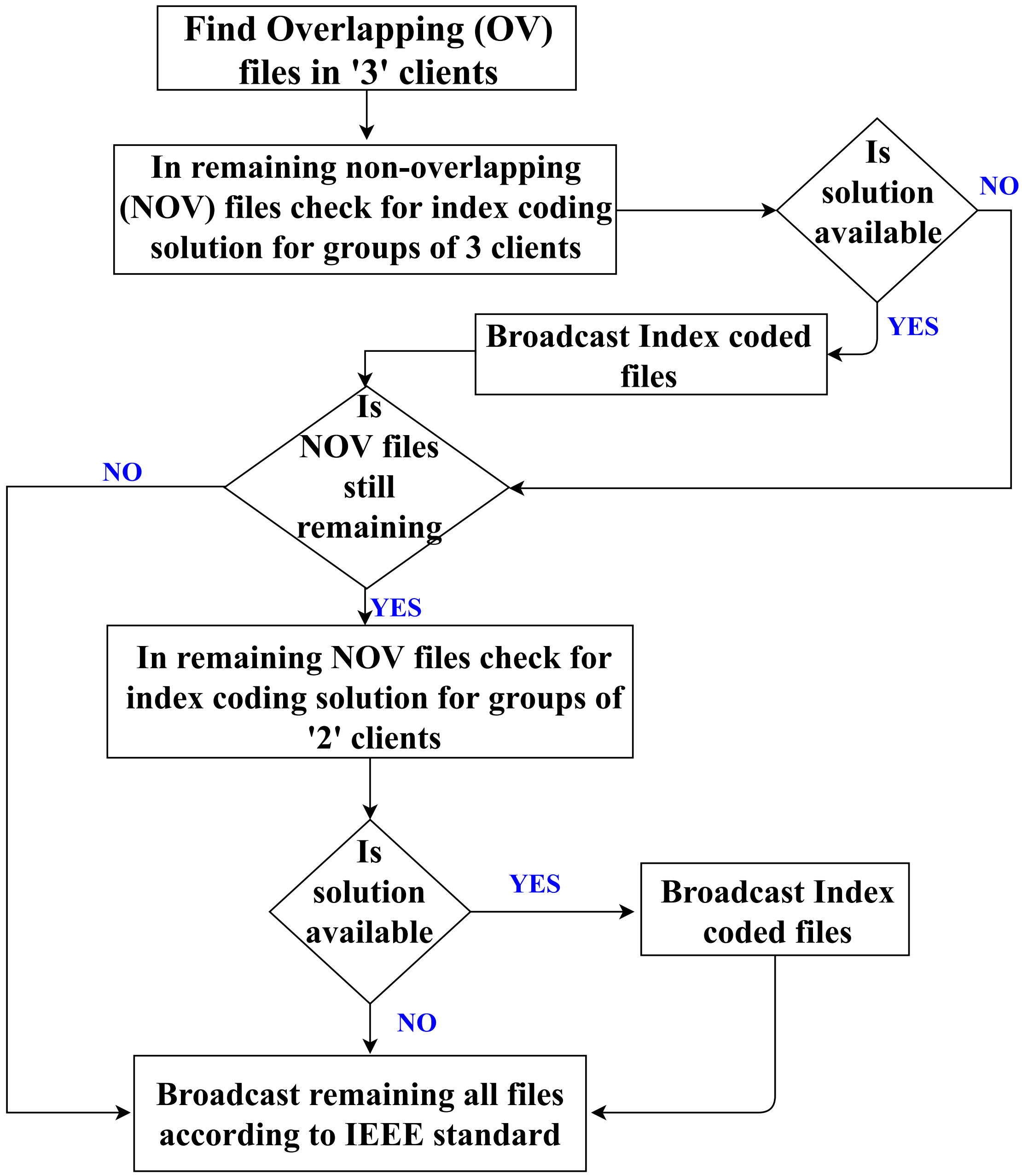


Figure 3.10: Flow chart of I-MERLIN server

shows operation of server, which beacons number of available files in the medium. After that, it starts listening to medium to check requests from various clients and then broadcasts requested files after processing. Once it receives requests from various clients, it processes them and transmits coded data files in the medium. Server interrupts its ongoing transmission and again starts listening to medium after transmitting some specific amount of files or for some specific time. The interrupt at server in ongoing transmission is to check for new client requests. After transmitting all requested files from available clients, server switches between beaconing and listening states to check for new clients in range. The operation of each client is shown in Fig. 3.9(b). When a new client enters in the transmission range of server, it is in listening state, so it either receives a beacon or overhears transmission from server. The client requests required files in the form of missing file ranges once it gets channel access. When client receives a file, it can be either an index coded file or non-coded file and client updates its repository if it receives required file and it can able to decode that file. Client is fully satisfied when it receives all requested files from server and switches to listening state when process is over.

After receiving requests from various clients, server processes them with respect to files available with it. The index coding decision is taken by server while processing requests from multiple clients. Fig. 3.10 shows the flow chart of the processing algorithm at the server when it processes requested files, and it is executed every time when server processes received requests. Server checks for overlapping (OV) and non-overlapping (NOV) files between clients, for NOV files, it checks for available index coding solution between groups of 3 and 2 clients. If solution is available, server broadcasts these NOV files by applying index coding.

3.3.3 Simulation Results and Discussion

The performance of I-MERLIN is verified in this section through various simulations performed in Matalb. The considered scenario is highway with RSUs similar with the one shown in Fig. 3.7. Since RSU is getting requests for missing files from nodes in the medium, it assumes that the not requested files are already present in the repository of requesting client. The contention based channel access mechanism is implemented for communication. By default, it is considered that server's repository is having 90% of total files, and all clients have initial repository content to be nearly 20%. Table 3.1 shows parameters used while performing simulations.

We consider multiple encounters with RSU, since all requested files cannot be downloaded by clients in a single encounter. The repository of clients gets updated in every encounter. Total files received by m^{th} client are given by equation 3.9. Where, R_{bo_k} are ranges of overlapping files between k clients, R_{bno_k} are ranges of non-overlapping files between k clients which can be index coded, π_m is the probabil-

Table 3.1: Simulation Parameters

Parameter	Value
Transmission Range of RSU	700m
Transmission Range of each node	500m
Number of files	1000
Server repository	90%
Client repository	20%
Average Speed of vehicles	100kmph
Number of packets per file	1000

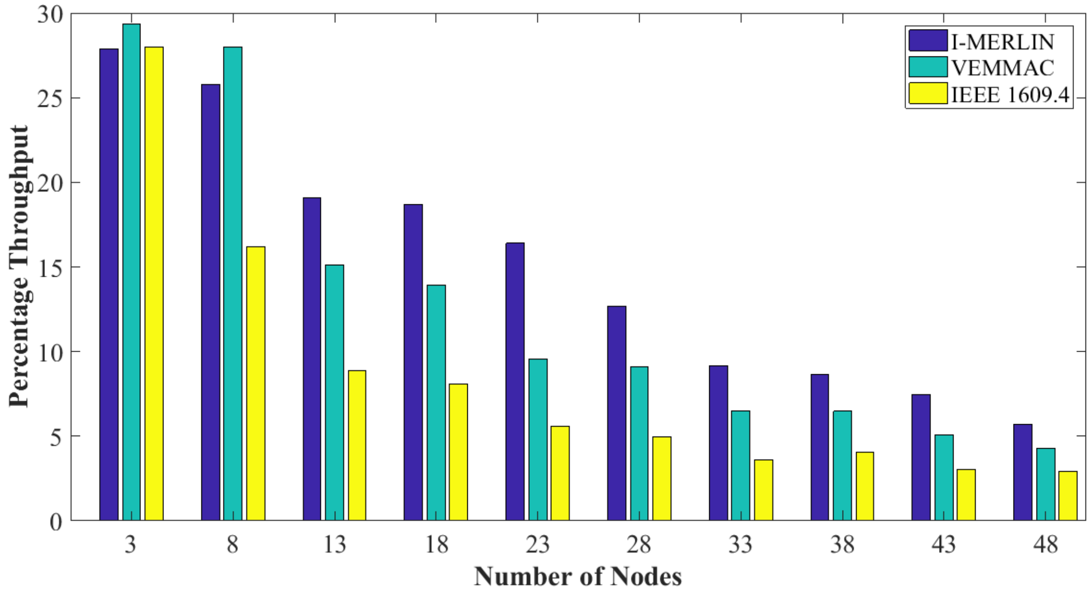
ity of occurrence of client m, r_m represents total ranges of files and R_{beno} are ranges of requested files remained after checking for all index coding combinations. The higher values of R_{bno_k} lead to better index coding possibility and reduced transmissions at server. Here, R_{bo_k}, R_{bno_k} and R_{beno} are the ranges of files present in server's repository and $U_{C_m}(R_{bm})$ is the summed output of all required files to m^{th} client which has R_{bm} contiguous ranges. Clients make requests in the form of file ranges to request more files in minimum requests. Server has to process requests from all clients and transmit those files after index coding. In equation 3.9, $U(R)$ notation actually gives number of files transmitted by server and R denotes ranges formed by server to deliver maximum requested data files.

$$d_{ri_m} = \frac{N_s}{N}\left[\sum_{k=1}^{r_m}\{U_{C_m}(R_{bo_k}) + U_{C_m}(R_{bno_k})\} + \pi_m U_{C_m}(R_{beno})\right] \tag{3.9}$$

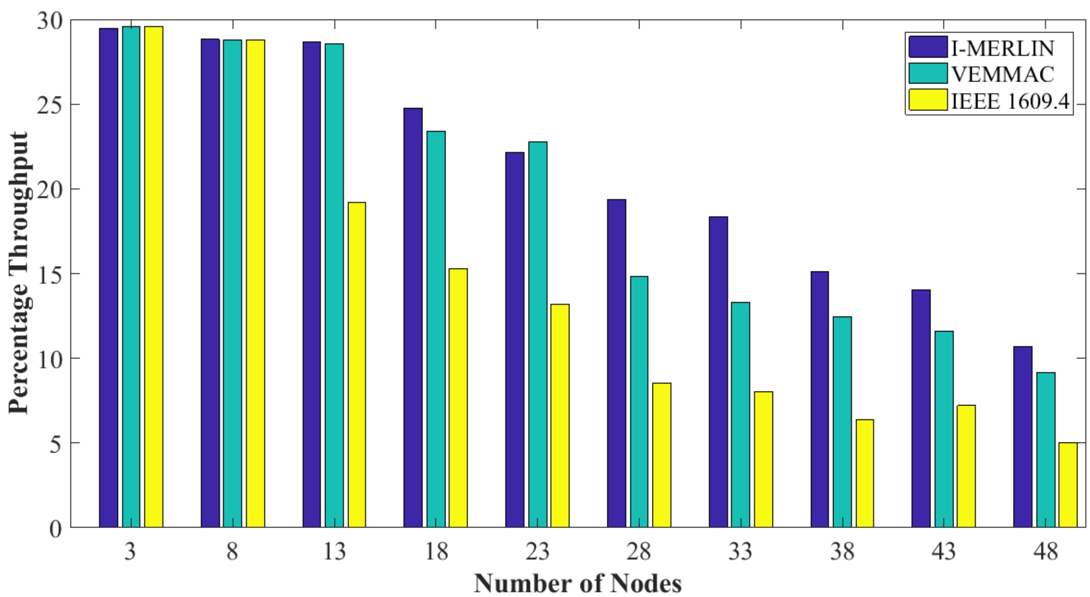
The performance is evaluated based on amount of data files transmitted by server over total encounter time and amount of bandwidth saved at server. The total number of data files received by all requesting clients which are transmitted by server over total encounter time is called as download throughput (or file delivery ratio of server). It is calculated as the ratio of total number of files received by all requesting clients to the total number of files requested by all clients over total encounter duration/time and it is given in equation 3.10. Total encounter duration is the sum of all encounter times of client-server communication. Simulations results are obtained for data received over 10 encounters. This value is chosen because at lower speeds of about 40 to 60 kmph, all the requesting clients receive files which are available with server within 10 encounters at that speed for 6 Mbps rate. It is stated that 6 Mbps is the optimal data rate for vehicular networks Daniel et al. (2008) and 3 Mbps data rate is mostly chosen in broadcast networks for robustness and reliability Claudia et al. (2011). Simulations are conducted under 3 and 6 Mbps data rates and results are plotted for the data received over ten encounters with RSU. The average speed of vehicle is considered to be 100 kmph for chosen highway scenario. The speed is used to consider the encounter time with RSU, since the encounter time varies according to speed and it is calculated by considering the residual time between vehicles for V2V communications.

The performance of I-MERLIN protocol is compared with IEEE 1609.4 and VEMMAC Dang et al. (2013). Fig. 3.11 and Fig. 3.12 show the percentage of total throughput obtained with respect to various clients requesting data from server with repository contents of 50% and 90% respectively. Here, vehicles, clients and nodes are the words used interchangeably for vehicles. All protocols perform nearly same for lesser number of clients, since for less number of clients there can be very less index coding combinations available, hence I-MERLIN performs nearly same as IEEE 1609.4. VEMMAC adopts IEEE 1609.4 and allows communicating nodes to transmit non-safety messages during CCH interval. It broadcasts safety messages twice within CCH interval and SCH interval which help in achieving higher throughput for service data. As VEMMAC uses part of CCH interval to transmit non-safety messages, this allows server to transmit more files, hence it achieves higher throughput than I-MERLIN for lesser clients. For lesser server repository content, the number of possible index coding combinations are less at server which reduces I-MERLIN performance even for higher number of clients. As rate increases, number of files transmitted by server increase, which improves number of files delivered. In VEMMAC and IEEE 1609.4, server transmits files directly without coding. I-MERLIN server takes some computation time to find out possible index coding combinations and transmits multiple files in a single file transmission. The computation time depends on number of available clients. For lesser clients in the medium there can be very less possibility of having index coding or no coding. For less number of clients in medium, VEMMAC performs better than I-MERLIN at higher rate, because of less index coding combinations. As server continuously broadcasts data files, the lost packets are not acknowledged for this case. Clients update their repositories every time they receive file from server. The information regarding lost packets is not available with server, but it can predict this information during next request by same client.

Fig. 3.13 gives the percentage improvement in throughput at various client speeds for different scenarios of available clients in the medium and 90% of initial repository



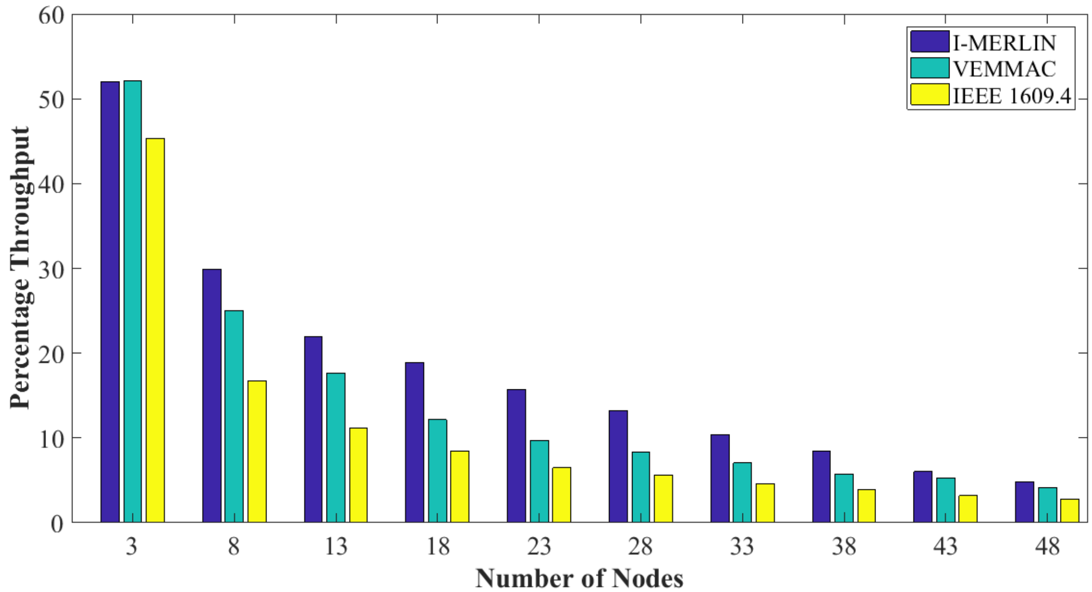
(a) Rate = 3 Mbps



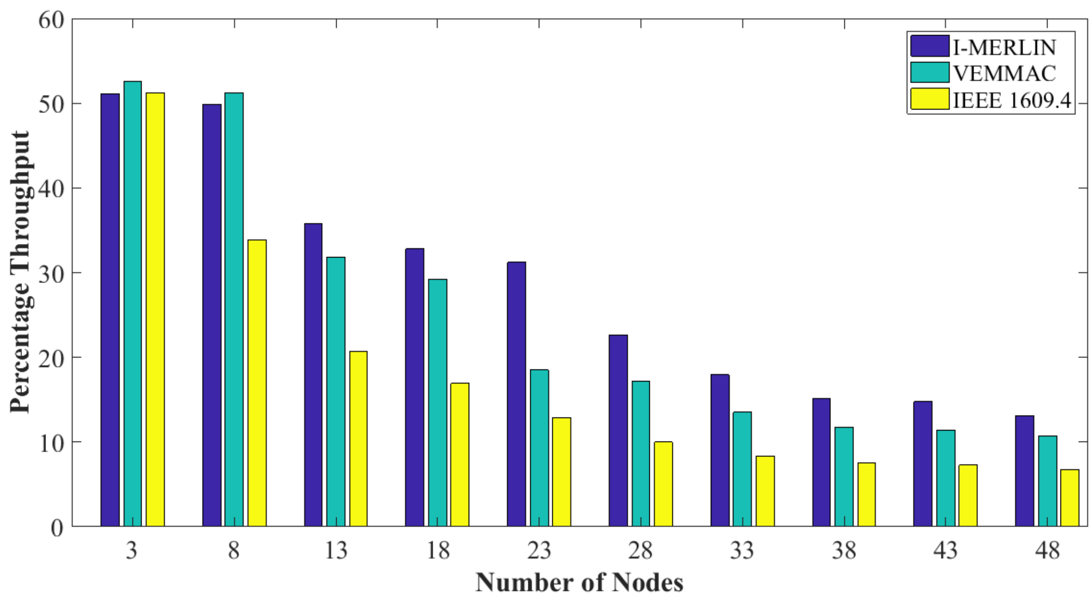
(b) Rate = 6 Mbps

Figure 3.11: Percentage throughput achieved with respect to number of available clients for server with 50% of initial repository content

content of server. The results for different scenarios are averaged and total numbers of clients considered for each scenario are in the range of 40 to 60. The results in Fig. 3.13 are plotted for 10 encounters with server at all speeds, hence the number



(a) Rate = 3 Mbps



(b) Rate = 6 Mbps

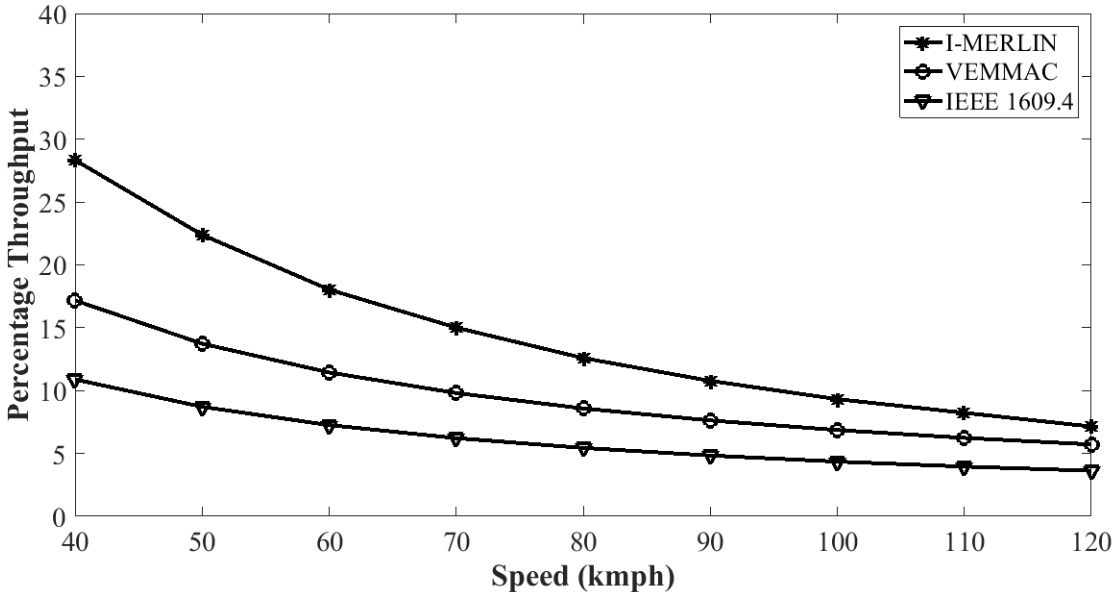
Figure 3.12: Percentage throughput achieved with respect to number of available clients for server with 90% of initial repository content

of files received in that time span are considered. The throughput is higher at lower speeds, since vehicles get more encounter time with RSU. But at higher speed, this time is less, also server has to process all the requests and encode within that time,

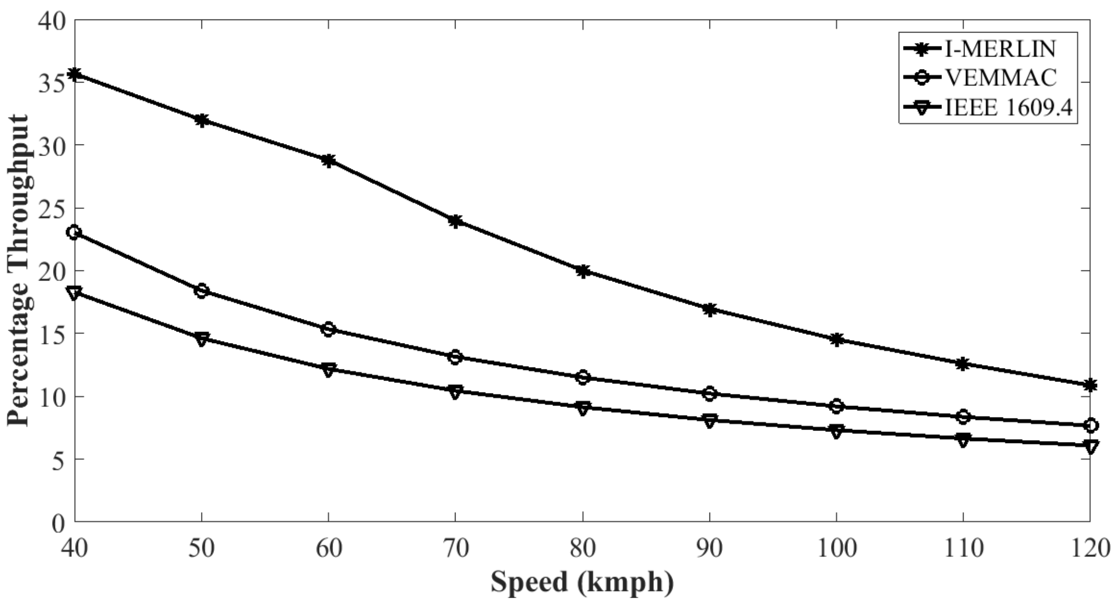
$$
\begin{aligned}
Download\ Throughput &= \frac{Total\ number\ of\ files\ received\ by\ all\ requesting\ clients}{Total\ files\ requested\ by\ all\ clients} \times 100 \\
&= \frac{\frac{N_s}{N}\sum_{m=1}^{M}\sum_{k=1}^{r_m}[U_{C_m}(R_{bo_k}) + U_{C_m}(R_{bno_k}) + \pi_m U_{C_m}(R_{beno})]}{\sum_{m=1}^{M}(N - N_{C_m})} \times 100 \\
&= \frac{N_s}{N}\sum_{m=1}^{M}\frac{\sum_{k=1}^{r_m}[U_{C_m}(R_{bo_k}) + U_{C_m}(R_{bno_k}) + \pi_m U_{C_m}(R_{beno})]}{(N - N_{C_m})} \times 100
\end{aligned}
\tag{3.10}
$$

so there is reduction in throughput at higher speed. The server repository content is considered to be 90%, so there are more index coding combinations available in this case, which eventually gives higher throughput for I-MERLIN. The adaptive SCH interval in VEMMAC gives nearly same or higher throughput as speed increases. In case of I-MERLIN, even clients receive nearly same number of files as in IEEE 1609.4 but one file transmitted from server can satisfy multiple clients which eventually gives higher throughput. VEMMAC achieves higher throughput when total files received using I-MERLIN are less than VEMMAC, this happens when there are very less index coding combinations available. It is observed that, I-MERLIN performs better than uncoded transmission schemes even at higher speeds.

The index coded technique used in I-MERLIN saves transmission bandwidth at RSU, since encoded file transmits 2 or 3 files in a single file. The percentage of bandwidth saved by I-MERLIN is given by equation 3.11. Here, IcF_3 and IcF_2 represent number of files transmitted with index coding *three* and *two* files respectively. Fig. 3.14 and Fig. 3.15 show percentage of bandwidth saved by I-MERLIN and VEMMAC servers over IEEE 1609.4 at various speeds for initial server repositories of 50% and 90% respectively. The bandwidth saved by VEMMAC increases with transmission rate since it transmits every file through adaptive SCH interval, whereas in I-MERLIN, multiple files are encoded in a single file and transmitted in SCH interval. As number of clients go on increasing, the saved bandwidth stays constant in I-MERLIN because of saturated index coding combinations and increased number of requested files. In VEMMAC, we consider files transmitted in CCH interval are the additional files transmitted which saves bandwidth for next transmission.



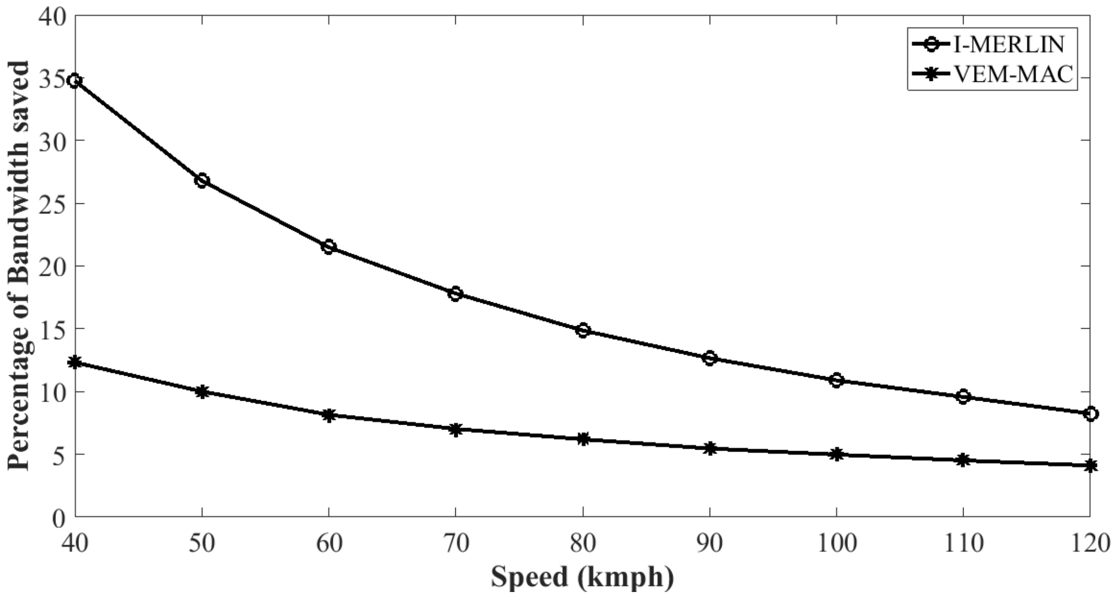
(a) Rate = 3 Mbps



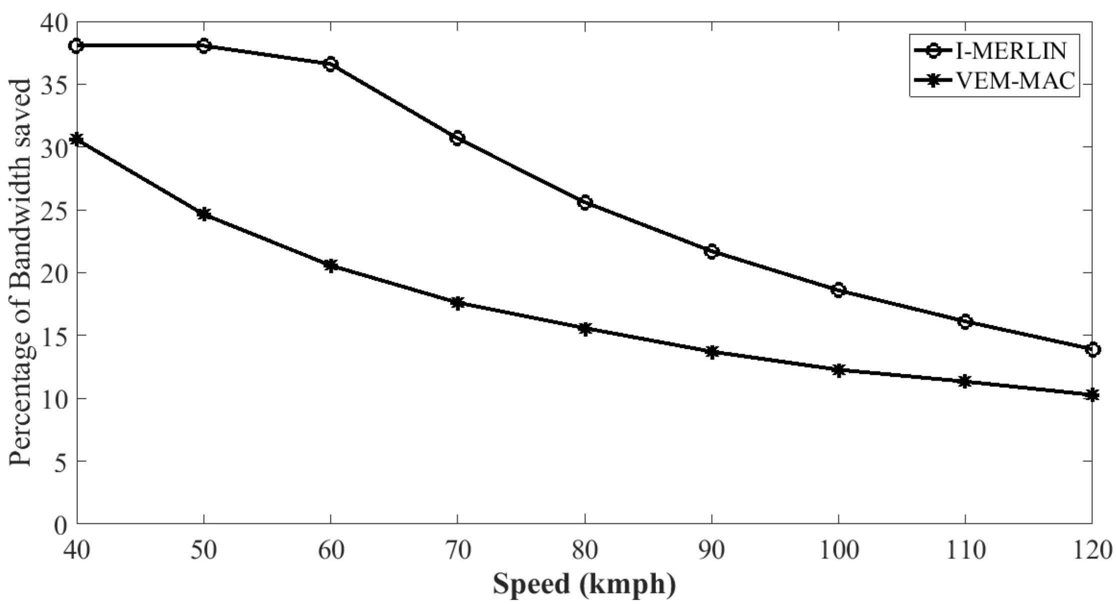
(b) Rate = 6 Mbps

Figure 3.13: Percentage improvement in throughput with respect to speed for 90% initial repository contents of server

$$
\begin{aligned}
&\textit{Percentage of bandwidth saved} \\
&= \frac{\textit{Total files saved from transmission}}{\textit{Total files requested by all clients}} \times 100 \\
&= \frac{2IcF_3 + IcF_2}{\sum_{k=1}^{M} (N - N_{C_k})} \times 100
\end{aligned} \tag{3.11}
$$



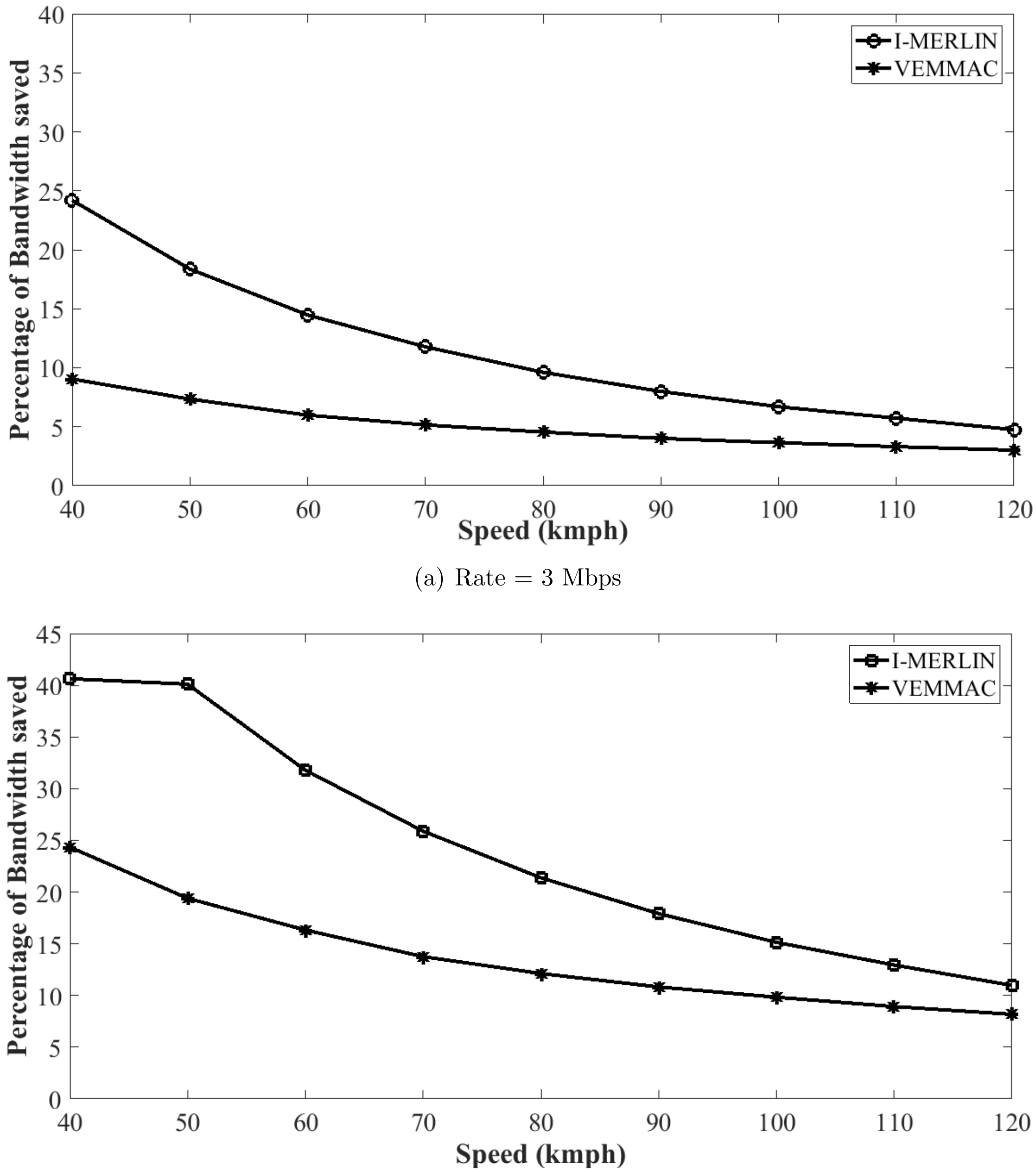
(a) Rate = 3 Mbps



(b) Rate = 6 Mbps

Figure 3.14: Percentage of bandwidth saved in I-MERLIN and VEMMAC over IEEE 1609.4 for number of clients= 35.

At very high speed and higher number of available clients, there is very less bandwidth saved. This is because the RSU is stationary and vehicles are having very high velocity which leads to very short encounter time with RSU. This issue can be



(a) Rate = 3 Mbps

(b) Rate = 6 Mbps

Figure 3.15: Percentage of bandwidth saved in I-MERLIN and VEMMAC over IEEE 1609.4 for number of clients= 50.

resolved through cluster based communication, where all vehicles are traveling with minimum relative speed between them and the vehicle with higher repository content can act as servers to fulfill demands of all its cluster members. Results show that

I-MERLIN outperforms IEEE 1609.4 as well as VEMMAC scheme in terms of download throughput and bandwidth saving. This protocol is suitable in dense scenarios, since reduction in number of transmissions avoid packet flooding in denser networks. Index coding is applied only when there is side information available, for that reason we consider some initial repository content available with clients. Even though there is no initial content available in the repository of client, server transmits data files following IEEE 1609.4 standard without applying index coding, since there is no side information available. After receiving some sets of files, clients request required data with respect to updated repository content. For every new requests server checks for side information to apply index coding and these updated clients repositories help server with the side information. For very high speeds, maintaining connectivity is one of the main issues in communication. This solution can be applied for any kind of data, not necessarily similar, provided that server has most of the requested data and receives awareness about repository of each client.

3.4 Improving data transfer using cluster based approach

In this section, a cluster based approach is incorporated to I-MERLIN. Here, clients can communicate between themselves and share data by forming clusters. Scenarios where server/RSUs are sparsely placed, clients cannot receive all the requested files in a single encounter from RSUs. For such scenarios, a cluster based approach is implemented in this section.

3.4.1 Description

Vehicles request required data to RSU and update their repositories with data received from RSU (if RSUs are present). After receiving data from RSU, vehicles start to communicate between themselves and share data by forming clusters. Clusters can be formed by considering various parameters such as cluster lifetime and relative speed between vehicles. Relative speed is nothing but the difference between speeds of two vehicles traveling in same direction, if vehicles are traveling in opposite direction, relative speed is the addition of speeds. For lower values of relative speed, vehicles have more encounter time within themselves, which lead to stable clusters. If clusters are

Direction of travel (L or R)	Percentage of available repository content	Previous CH identifier (PCHID)	Speed

Figure 3.16: Packet structure used for information exchange during cluster formation

formed between vehicles moving in same direction, more encounter time is available for cluster members and cluster stability can also be maintained. In the absence of RSU, all vehicles exchange information regarding their direction of travel, percentage of available repository content, previous cluster head (CH) identifier (PCHID) and speed. Fig. 3.16 shows structure of packet used to exchange information while forming clusters. The direction of travel is indicated by left (L) or right (R) direction. The PCHID field is '0' (zero) if cluster is formed for first time or the cluster doesn't have a CH. Using this information vehicles traveling in same direction start forming clusters. The relative speed between vehicles traveling in the same direction is less which eventually creates more stable cluster and give more time for information exchange.

The CSMA/CA mechanism is implemented between vehicles to get channel access. Once a vehicle gets channel access, it shares packet for information exchange. After receiving packets from various members, the vehicle with higher repository content and direction send one acknowledgment packet confirming CH status and direction of travel. Other vehicles travelling in the direction of CH vehicle start acting as clients. The elected CHs sends their ID along with acknowledge message. This helps vehicles in the cluster to receive data from that particular ID, which could eventually help reducing inter-cluster interference.

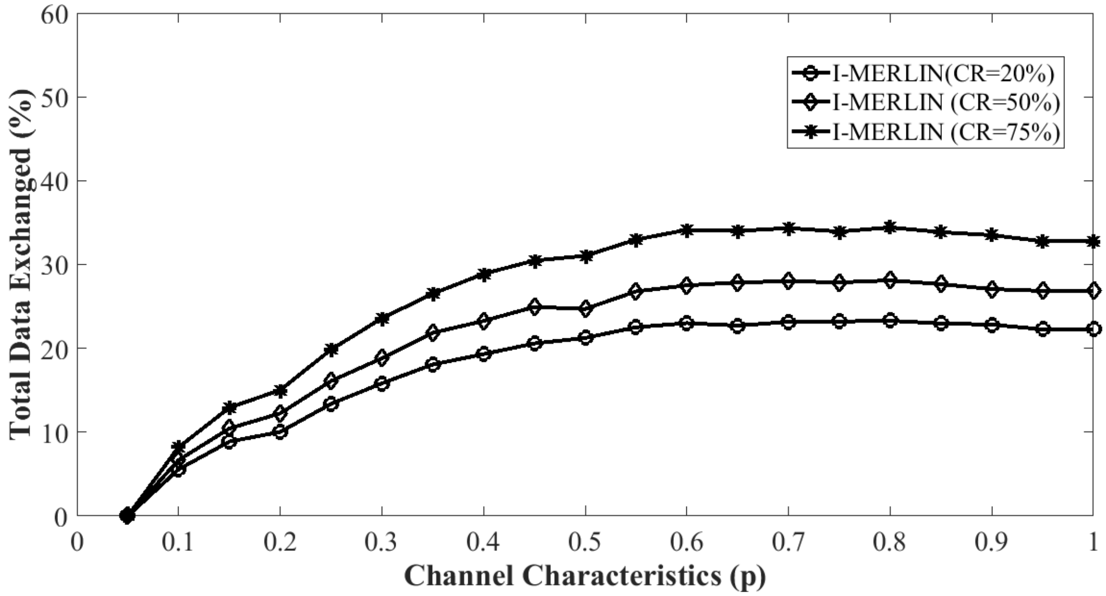
Once the clusters are formed, the cluster head (CH) can act as server and it is accepted by all cluster members by exchanging the information about their repositories. Here, we are electing a CH, which has average speed as well as more repository content so that the CH can satisfy demands of its cluster members to a higher extent. Here, CH is a source node (server) and all other nodes act as destination (clients). After CH is elected, it changes its state from client to server. All members of cluster request required data to the CH and CH processes those requests and applies index coding solution to transmit multiple files in minimum transmissions. Once CH finishes transmission of all files with it, it sends an acknowledgment packet saying that it has finished transmission of files. The same procedure is continued to form a new CH. If current CH is the one with higher repository content, then the new CH is elected with next higher repository content. Here, each vehicle can act as server as well as client and it depends on the state of vehicle and its repository content.

3.4.2 Simulation Results

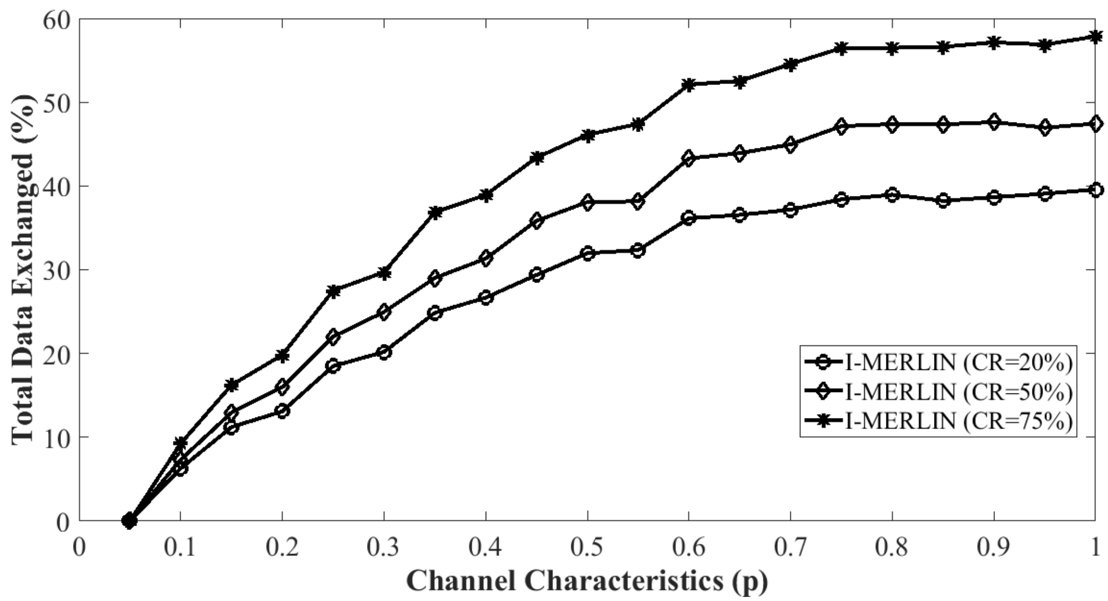
The proposed cluster based approach is implemented in Matlab with the similar assumptions and simulation parameters used in previous section. RSU/Server's repository content is considered as 90% of total files available, and all clients are considered to have various initial repository contents in range of 20% to 75%. The considered scenario is highway with very sparsely located RSUs. Hence, one encounter with RSU is considered for all clients and they update their repository with files received from RSU in a single encounter using I-MERLIN. After this clients start forming clusters and data exchange between themselves as explained above. The data loss in the channel is due to various effects in that channel. Channel characteristics (p) is used to consider effects of channel, values for p stand between 0 to 1 Bharati and Zhuang (2012). The value of p denotes the amount of successful transmission, for example $p = 0.7$ means 70% of the total transmissions are successfully received. The amount of data exchange happened through cluster formation is measured for various client repository (CR) contents under different channel characteristics.

The percentage of total data exchanged between the formed clusters using I-MERLIN for various channel characteristics is shown in Fig. 3.17. These results are obtained at average speed of 80 to 100 kmph and at various clients repository contents, maximum client repositories to be 20%, 50% and 75% as shown in Fig. 3.17. Fig. 3.17(a) and 3.17(b) show total amount of data exchanged between cluster members when number of vehicles in the medium are nearly 50 and 100 respectively. For worse channel characteristics, the successful transmissions in the allocated slot are almost zero so there is more data loss in the medium. At good channel characteristics, the probability of error-free transmission increases which gives more efficiency of data exchange. As number of vehicles go on increasing the randomness of data available with each client increases which eventually increase amount of data exchanged between vehicles. The percentage of total data exchanged is calculated as a ratio of total amount of data received to total amount of data requested over various channel characteristics.

Clusters are formed between vehicles moving in same direction randomly in groups of 10 to 12 cluster members and results are plotted for total data exchanged between all clusters. As vehicles are moving in same direction, the relative speed is minimum and



(a) Nearly 50 vehicles are there in the medium



(b) Nearly 100 vehicles are there in the medium

Figure 3.17: Percentage of data exchanged against various channel conditions for different client repository (CR) contents available

also more time is available for data exchange. I-MERLIN is applied to the cluster based data transfer and only clients with different repository contents act as servers. This CH/server selection procedure helps to satisfy multiple clients in an organized way instead of point-to-point communication between clients. The information regarding change of path or disconnection of any cluster member is considered during new CH or cluster formation after current CH finishes its ongoing transmission. Similar procedure is followed if a new client wants to join a cluster. If CH wants to disconnect from the cluster, it informs to all cluster members through a beacon message. It is observed that, minimum relative speed gives more time for data exchange which eventually increases amount of data exchanged.

3.5 Summary

We presented design and analysis of I-MERLIN protocol in this chapter. I-MERLIN is developed to increase amount of data delivered over network in lesser transmissions. The use of index coding reduces number of transmissions at server which eventually saves transmit bandwidth. More data can be delivered with use of index coded transmissions and download throughput is measured at client based on number of received files which are completely decoded. Performance is verified under different client and server initial repository contents. CCH is reserved only for safety information and SCH is used for non-safety information transfer. The cluster based approach for data exchange between vehicles is presented, where RSUs are sparsely placed. Proposed I-MERLIN protocol achieves better data download throughput (or data delivered by server) compared with other techniques and saving in transmission bandwidth is achieved over IEEE 1609.4 standard.

Chapter 4

DECENTRALIZED CONGESTION CONTROL IN VANETs

The regular exchange of safety and alert messages, also called as Cooperative Awareness Messages (CAMs) leads to congested medium. Decentralized Congestion Control (DCC) techniques are proposed by European Telecommunications Standards Institute (ETSI) to overcome above situations in a fair and decentralized manner. DCC adapts various transmission parameters based on current situation as well as surrounding constraints. It works by considering parameters at different layers and hence DCC is a cross layered approach used to reduce congestion in communication medium. ETSI has defined various components under cross layered DCC function, location and linking between these components is defined in ETSI (2011). Transmit Rate Control (TRC), Transmit Power Control (TPC) and Transmit Data-rate Control (TDC) are defined access layer mechanism by ETSI which adapt transmit message rate, power and data-rate respectively. Clear Channel Assessment (CCA) is used to solve local channel congestion under DCC Sensitivity Control (DSC). High priority packets such as critical safety information need to be communicated with minimum delay, Transmit Access Control (TAC) and transmit queuing concept are defined to transmit these type of messages with minimum restrictions.

ITS-G5 defines set of protocols along with various parameters for highly dynamic VANETs specified by ETSI. ITS-G5 radio takes networking and transport layer decisions based on the available information regarding medium and various transmission parameters ETSI (2011), ETSI (2014). DCC is specified to be a paramount component of an ITS-G5 station under ETSI. The DCC-Access, DCC-Net, DCC-Facility and DCC-Management are layers spanned by ITS-G5 station. The decentralized approach of DCC follows three states called relaxed, active and restrictive depending on channel congestion. Congestion is measured in terms of available channel load (CL) and DCC adapts transmission parameters based on current channel load. The process is said to be in *active* state, if current CL is more compared to the defined minimum CL (minCL) and less compared to the defined maximum CL (maxCL). When the congestion is very less, the process is in *relaxed* state i.e., the CL is less than minCL in relaxed state. Once current CL exceed the threshold value of CL (i.e. maxCL), it is supposed that the medium is congested and the CL beyond maxCL, can't be handled efficiently, hence it is called as *restrictive* state. Fig. 2.1 from chapter 2, shows state transition diagram for DCC_access layer with the states discussed above.

DCC protocols are developed by adapting various transmission parameters related to physical and link layers. The information can be exchanged in minimum latency if the channel congestion is reduced and the high priority safety critical messages can be delivered quickly. Transmit power is adapted based on channel congestion under TPC mechanism. Transmit power is the physical layer parameter, it affects the communication range, message reception based on receiver sensitivity and channel interference. Message rate and data rate are link layer parameters and controlling these parameters depend on the required application. Safety messages are frequently transmitted messages or beacons, hence message/beaconing rate control is used for safety applications. Infotainment applications such as audio/video transfer or transferring large files over the medium needs more bandwidth and this can be achieved by controlling data-rate or controlling multiple parameters together. We propose two techniques which include combined power control mechanisms along with data-rate and message-rate control under two-state active design of DCC.

4.1 Proposed work

The combined power control along with other parameters makes DCC technique to be environment and context aware. ETSI proposed a multi-state active design in which the *active* state in Fig. 2.1 is divided into multiple active states. In this work, two-state active design shown in Fig. 4.1 is used to implement proposed mechanisms.

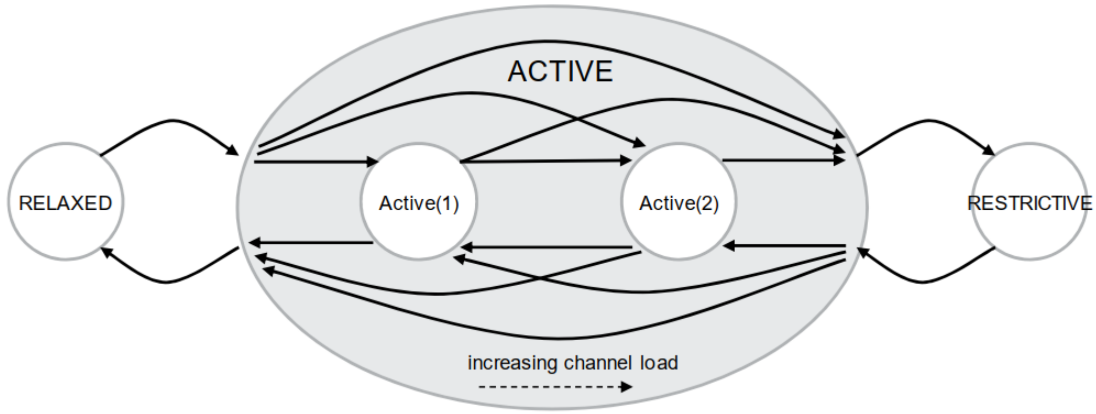


Figure 4.1: Two state active DCC_access state transition diagram ETSI (2011)

The two state active design shown above uses two different thresholds for CL under each state. Channel Busy Ratio (CBR) is the metric used to measure congestion in DCC techniques. CBR can be calculated as ratio of length of all messages received by ego vehicle (in bytes/sec) to the channel capacity (in bytes/sec) as shown in equation 4.1 Aygün et al. (2015). Here, total number of available neighbors are M, l_k is the length of message received from k^{th} neighbor in $bytes/sec$ and C is channel capacity in $bytes/sec$. Ego vehicle is the term used for a particular node in the medium, all analysis and calculations are done with respect to ego vehicle. CBR calculations are done at ego vehicle by analyzing information related to messages received from its neighbors. Threshold values for CBR are considered between 0.2 to 0.43 for active state 1 and CBR between 0.43 to 0.6 as active state 2. The system in Fig. 4.1 is considered in *Relaxed* state when $CBR < 0.2$, the system is considered in *Active(1)* when $(0.2 \leq CBR < 0.43)$, for $(0.43 \leq CBR < 0.6)$ *Active(2)* state is reached and for $CBR > 0.6$ the system is considered in *Restrictive* state. The value 0.43 is randomly chosen here as a threshold value for active state 1 and active state 2. The intention behind this value instead of center value 0.4, is to keep the system away from congestion for more time (that is in active state 1). Another reason is to avoid drastic changes (oscillation) in adapted message rate values. Different threshold values lead to different adaptation patterns and variation in CBR. Two algorithms based on message rate adaptation and data rate adaptation combined with power control are proposed in this section.

4.1.1 Combined Power and Message-Rate Adaptation (CPMRA)

The received power level at a vehicle gives, type of channel and loss in medium. The multipath fading, reflections and environment are the factors affecting received power. These effects lead to heavy data loss as density increases, which may cause channel congestion. The use of power adaptation mechanisms based on received power due to environment and fading effects help in understanding channel loss and can eventually reduce congestion. If density is high, only power control may not solve the issue of congestion, message-rate or data rate control along with power control can help in a much better way to tackle the congestion issues.

$$
\begin{aligned}
&\textit{Channel Busy Ratio (CBR)} \\
&= \frac{\textit{Sum of lengths of messages received from each neighbor(bytes/sec)}}{\textit{channel capacity (bytes/sec)}} \\
&= \sum_{k=1}^{M} \frac{l_k}{C}
\end{aligned}
\tag{4.1}
$$

A combined power and message-rate adaption (CPMRA) mechanism is presented, the power control mechanism is used to consider environment awareness and fading effects, whereas the message rate is controlled based on the value of CBR for efficient and error free transmission. ETSI have specified transmit message rate to be in range of 1 Hz to 10 Hz. In CPMRA mechanism, power and message rate are adapted based on current CBR value so that the congestion is maintained within specified limits. The ego node calculates CBR value using equation 4.1 based on amount of data received from its neighbors. If CBR is below threshold, CPMRA increases message rate using equation 4.2 (maximum up to 10 Hz). Similarly, if CBR exceeds the threshold value, message rate is decreased according to equation 4.3. Here, $R_i(t-1)$ is the message rate at previous time step, $R_i(t)$ is the increased message rate and $R_d(t)$ is the decreased message rate at time t for the ego node, $CBR(t)$ and CBR_{Th} are CBR found by ego node at time t and threshold CBR respectively. The *sign* function returns $+1$ if the entity is greater than zero and it returns -1 if the entity is less than zero. Convergence factor α and adaptive gain factor β are jointly used for algorithm convergence and have converged values to be $\alpha = 0.1$ and $\beta = 1/150$ Bansal et al. (2013). X is a threshold saturation gain and is found based on message size, rate, channel capacity and α. In our case, the value of X is 0.00416 and it is calculated as the ratio of message rate to α multiplied with channel capacity in messages/sec. The target increased rate is $min[10, R_i(t)]$ and the target decreased rate is $min[10, R_d(t)]$.

$$R_i(t) = (1+\alpha)R(t-1) + \{sign(CBR_{Th} - CBR(t)) \times min[X, \beta(CBR_{Th} - CBR(t))]\} \tag{4.2}$$

$$R_d(t) = (1-\alpha)R(t-1) + \{sign(CBR_{Th} - CBR(t)) \times min[X, \beta(CBR_{Th} - CBR(t))]\} \tag{4.3}$$

The active-1 state in state transition diagrams shown in Fig. 4.1, indicates less amount of congestion compared with active-2 state. So, if system is in relaxed or active-1 state, it can still handle increase in message rate. In active-2 state, increase in message rate can lead system to restrictive state. To maintain the system in active state and congestion in specified limits, value of α is chosen to be $'0.1'$ and $'0.05'$. These values are used to increase or decrease message rate. For system in relaxed state, α is chosen as 0.1, and for system in active state 1, it is chosen as 0.05 in equation 4.2. When system is in restrictive state, α is chosen to be 0.1 in equation 4.3. This can help in utilizing channel to more extent by keeping system in active state for more time. The message rate adaptation algorithm is applied to all four states of two-state active design of DCC.

The power control algorithm is applied at ego node based on the CBR value as well as current neighbors and environment conditions. Ego node calculates its distance from each neighbor and selects only those neighbors which are in its target awareness range. The awareness metric is used to measure the awareness about ego vehicle by its neighboring vehicles and ego vehicle estimates it locally. The ego vehicle calculates the transmit power required at time instant $(t+1)$ (or the value for next time step) using path loss exponent and path loss for messages received from its neighbors. These metrics give information related to channel conditions and fading due to multipath reflections. The power control algorithm considers number of neighbors in target awareness range, and it executes for every simulation time step. If ego vehicle has same neighbors as previous time step and CBR is less than threshold, algorithm uses same transmit power in next observation interval (or time step). The required power for next step to reach each neighbor is calculated from equation 4.4. Here, M denotes total numbers of neighbors of ego vehicle, $P_j^{Rx}(t)$ is power received from j^{th} neighbor for current time interval, $PLE_j(t)$ is path loss exponent for current time interval, λ is wavelength and $r(t)$ is target awareness distance of ego node. The received power from every neighbor is calculated and the maximum value of $P(t+1)$ is chosen by considering the effect of target awareness percentage Aygün et al. (2015).

$$P(t+1) = \frac{1}{M}\sum_{j=1}^{M} P_j^{Rx}(t) + 10PLE_j(t)\log_{10}\left(\frac{4\pi}{\lambda}r(t)\right) \tag{4.4}$$

The working flow of CPMRA for a single time step is shown in Fig. 4.2. The available number of neighbors within target awareness range and received power from each neighbor is calculated at ego node. From these available values, CBR and transmit power required for next time step are calculated. Once these values are calculated, adaptation algorithm is applied based on number of available neighbors and CBR value. The state of system is obtained from current CBR value and the α value is chosen from current state of the system. The received power for current time-step is calculated for some set of available neighbors, the power adaptation is applied for next time-step if the CBR value exceeds the threshold value for same number of neighbors. If number of neighbors for next time-step are changed, power adaptation is applied for next time-step irrespective of CBR value. The change in neighbors enforce extra processing to set up communication links, hence the power adaptation is applied for that case. The message rate adaptation is applied depending on the values of current CBR. In current time step, if the CBR value exceeds threshold value for a particular state, depending on that DCC state and CBR value, the message rate is selected for next time step as explained earlier. In every time step, ego node performs above procedure and accordingly use newly calculated power and message rate values for next time step.

4.1.2 Combined Power and Data-Rate Adaptation (CPDRA)

The data contained in larger data files or entertainment data, playing online games are the applications needing more bandwidth and data rate for communication. In high density networks, these applications can cause congestion due to its requirements of data rate and bandwidth, this can sometimes delay the safety message delivery.

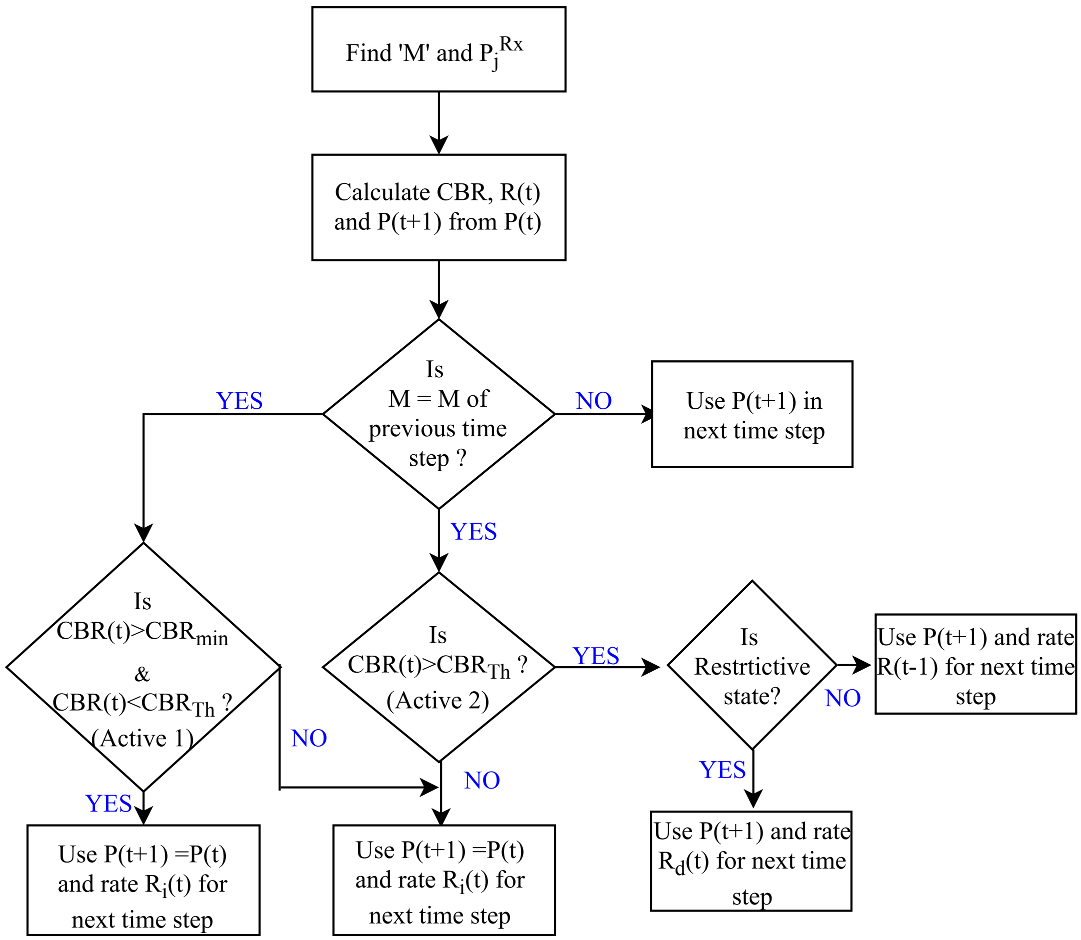


Figure 4.2: Flow chart for a single time step of CPMRA

The combined power and data-rate adaptation mechanism is proposed in this section to tackle issues related to infotainment data transfer. The data-rate and power are adapted depending on the current congestion situation. The power control mechanism is same as CPMRA algorithm, ego node changes transmit power based on available neighbors and CBR values.

The broadcasting network causes flooding for higher data rate values in dense scenarios. The evaluated data rate for broadcast network is 6 Mbps Daniel et al. (2008) and 3 Mbps data rate is mostly chosen for dense broadcast networks. The data rate values are selected depending on current channel congestion so that more data can be transmitted over the channel with minimum data loss. Table 4.1 reflects data rates adapted for CBR values under different DCC states. Higher data rate is allocated for the relaxed state because at minimum congestion level, data transferred at higher rate guarantees fast and reliable transmission. In relaxed state, the number of vehicles in the medium is less and channel is almost free, so the data can be transmitted at higher rate. As the CBR value goes on increasing, the data rate is reduced depending on the threshold CBR value and DCC state. This data rate adaptation mechanism adjusts the communication bandwidth to avoid data loss and more data delivery. The probability of failed transmissions as well as long queues can be reduced. Increasing number of neighbors increase possibilities for various calamities which eventually increase number of safety messages. Hence, as CBR increases, the data rate is reduced so that the possibility of collision between safety messages can be reduced. Safety and beaconing messages are always transmitted at higher data rates.

Table 4.1: Adapted data rates from CBR value

CBR	**DCC State**	**Data rate (mbps)**
< 0.2	Relaxed	12
$>= 0.2$ & < 0.43	Active1	9
$>= 0.43$ & < 0.6	Active2	6
$>= 0.6$	Restrictive	3

The operation of CPDRA is explained in Algorithm 3, data rate adaptation is applied based on current CBR value and available number of neighbors. The data rate values are chosen from Table 4.1 for next simulation time step. The non-safety applications involve sharing of larger files as well as infotainment data. This data sharing happens between all neighboring vehicles, hence the CPDRA algorithm considers number of available neighbors in every time step. It is assumed that, for same number of available neighbors the data exchange is considered uninterrupted. If number of neighbors change, the data exchange may or may not continue due to absence of source or destination, hence same data rate is carried to next time step to establish new communication. The value of data rate depends on channel capacity and bandwidth which affects CBR. The transmit power control mechanism helps to consider fading effects caused by surrounding vehicles as well as other objects. So, this mechanism of directly choosing data rate based on CBR values is completely feasible for real world VANET scenarios.

Algorithm 3 Two-state active data-rate adaptation

Require: Simulation scenario generated from SUMO
1. Calculate number of neighbors and received power from each neighbor using GEMV^2.
2. *Calculate CBR*
if No. of neighbors=No. of neighbors in prevoius time-step **then**
  if $CBR < 0.2$ **then**
    $Data\ Rate = 12\ Mbps$
  else if $0.2 <= CBR < 0.43$ **then**
    $Data\ Rate = 9\ Mbps$
  else if $0.43 <= CBR < 0.6$ **then**
    $Data\ Rate = 6\ Mbps$
  else
    $Data\ Rate = 3\ Mbps$
  end if
else
  $Data\ Rate = Current\ Data\ Rate$
end if

4.2 Simulation results

This section presents simulation results for proposed two-state active DCC protocols. From the channel load, these protocols adapt message rate and data rate along-with power control mechanism. The two state active model used for simulation is shown in Fig. 4.1 and threshold values for each state are presented in Table 4.1. Simulation results are obtained using GEMV^2 V2V propagation simulator Boban et al. (2014). GEMV^2 is a computationally efficient propagation model for V2V communications, which considers effects of surrounding objects (e.g. foliage, buildings and vehicles Boban et al. (2011b)). Realistic mobility traces with Google-earth visualization are generated using simulation of urban mobility (SUMO) and route files are generated for simulation using these traces Krajzewicz et al. (2012). The scenario used for simulation is the area around Mangalore city in India, generated using *openstreetmap* and SUMO. Fig. 4.3 shows the generated scenario for simulation with 250 to 300 vehicles in the given area. Google-earth visualization is applied in SUMO to get the information about surrounding objects and foliages, so that GEMV^2 considers all reflections from surroundings and calculates required parameters for simulation. Filled circle in Fig. 4.3 indicates communicating vehicles and colored line are multipath reflections received from surrounding objects. Log-Normal model is used in GEMV^2 to analyze channel using these multipath reflections. Table 4.2 shows default values of some parameters considered in simulations.

Table 4.2: Simulation Parameters

Parameter	**Value**
Beaconing rate	10 Hz
Message size	250 Bytes
Carrier sense threshold	-90 dBm
Threshold Channel Busy Ratio	60% (0.6)
Measurement interval	200 ms
Transmit power	23 dBm

The two-state active system shown in Fig. 4.1 is used to simulate proposed CPMRA and CPDRA mechanisms, results are compared with available standard DCC protocols. The performance is evaluated based on variations in CBR, transmit power and message rate. The performance of CPMRA and CPDRA is compared with ECPR, TPC, TRC, TDC and without DCC mechanisms. CBR is calculated in each measurement interval and the adaptation is applied based on present channel load for all mechanisms. Fig. 4.4, 4.5 and 4.6 show simulation results obtained for all mechanisms for the scenario shown in Fig. 4.3. Results are obtained for set of initial transmit power and target awareness distance to be [23dBm, 90m] and [10dBm, 150m]. Fig. 4.4 shows results obtained for CBR and adapted message rate values for initial transmit power of 23 dBm and target awareness distance 90m. Fig. 4.5 shows results obtained for CBR and adapted message rate values for initial transmit power of 10 dBm and target awareness distance 150m. All results are obtained for target awareness of 85%. Results show that, both the proposed mechanisms keep channel load of system within specified limits. The rate adaptation in CPMRA has various oscillations because of different α values chosen for two active states. This oscillatory change in message rate in CPMRA utilizes more channel resources along with congestion control. The message rate control mechanism is not applied to CPDRA, TDC and TPC, hence maximum rate of 10 Hz is used during simulations. TRC and TDC mechanisms have used fixed initial transmit power to each node for all time steps of simulation.

Data rate adaptation mechanisms TDC and CPDRA use higher data rates at lower CBR values or in relaxed state of DCC system. Since channel capacity is directly re-

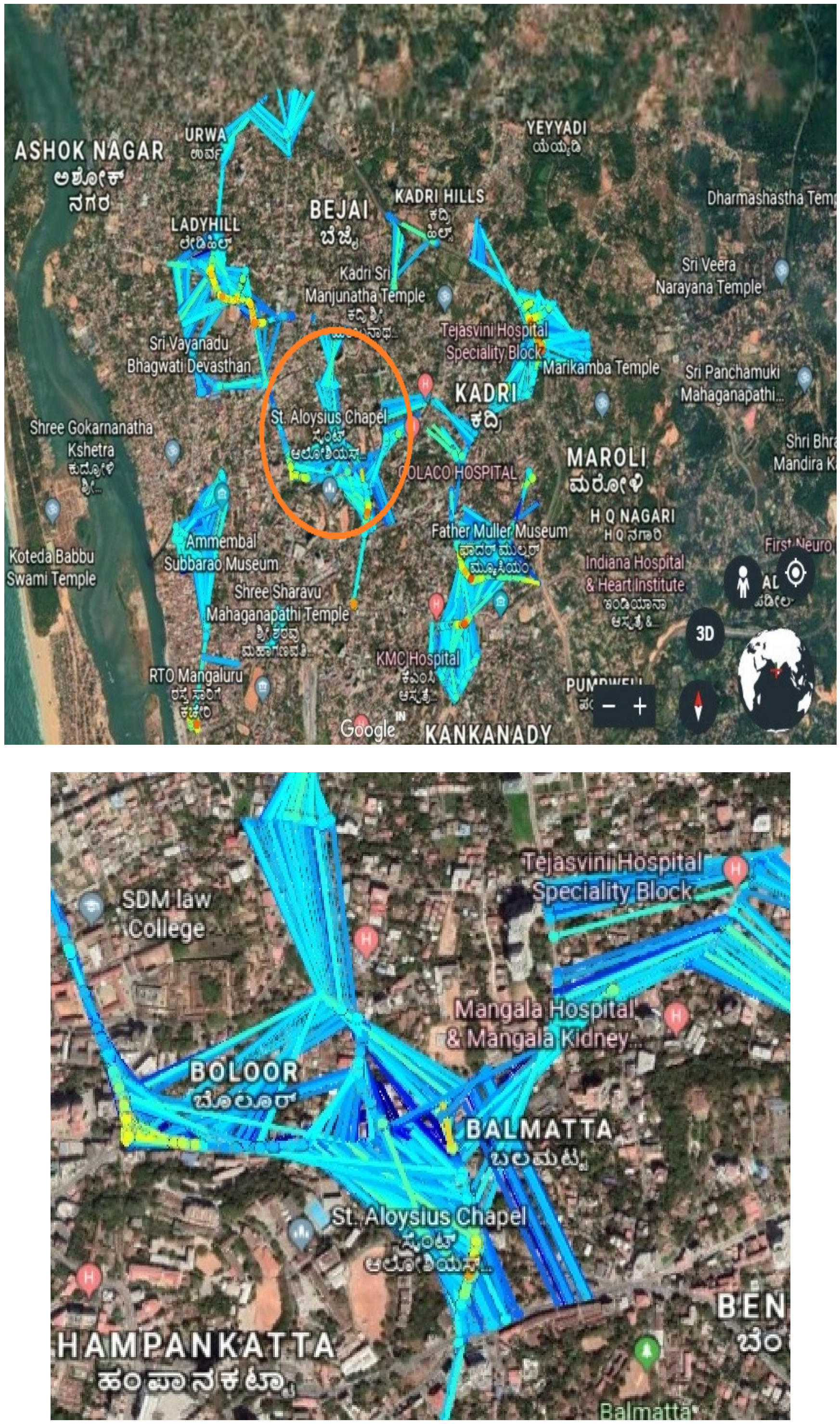
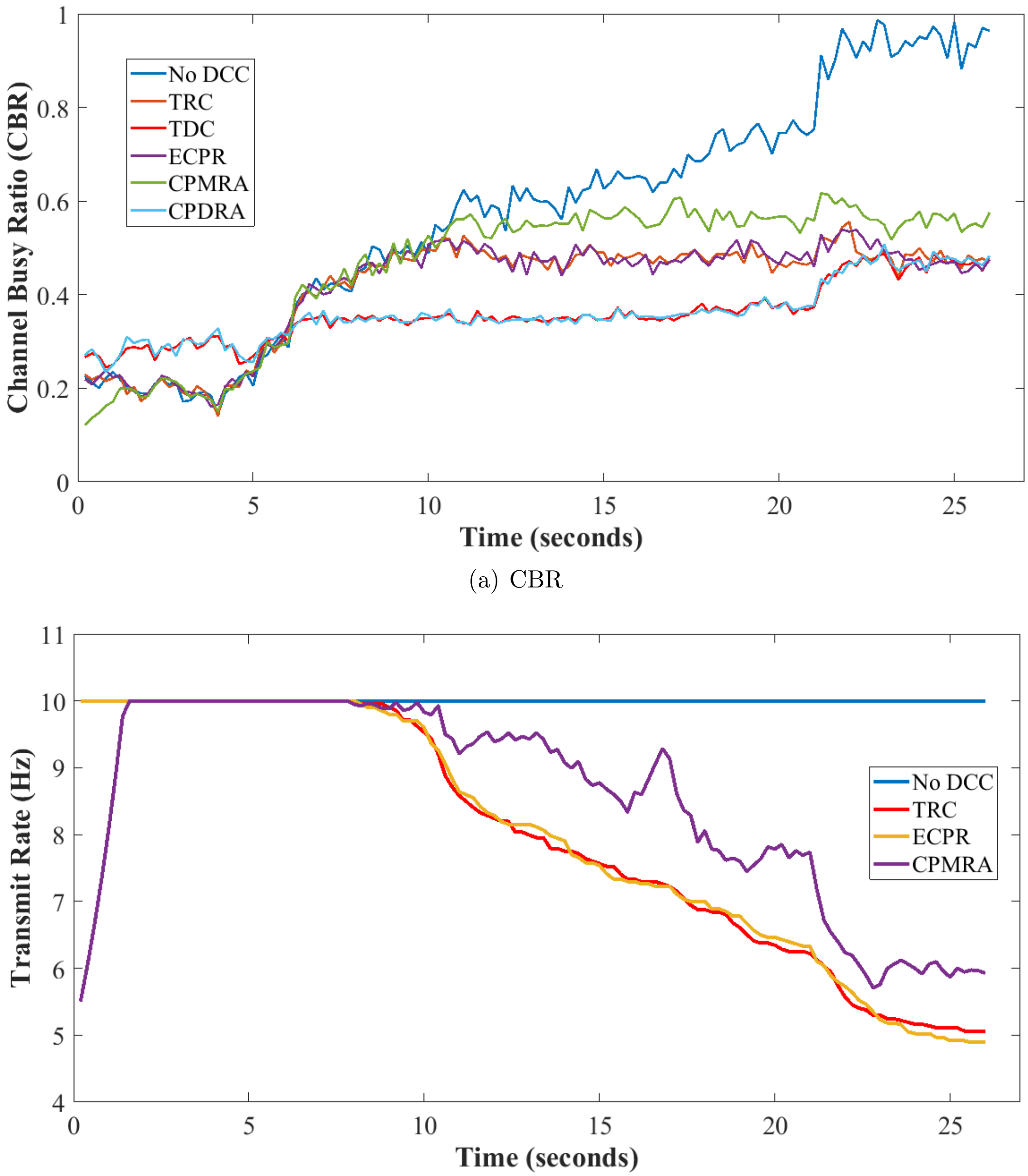


Figure 4.3: Simulation scenario generated from SUMO considering area around Mangalore. Second figure is enlarged view of circled area.

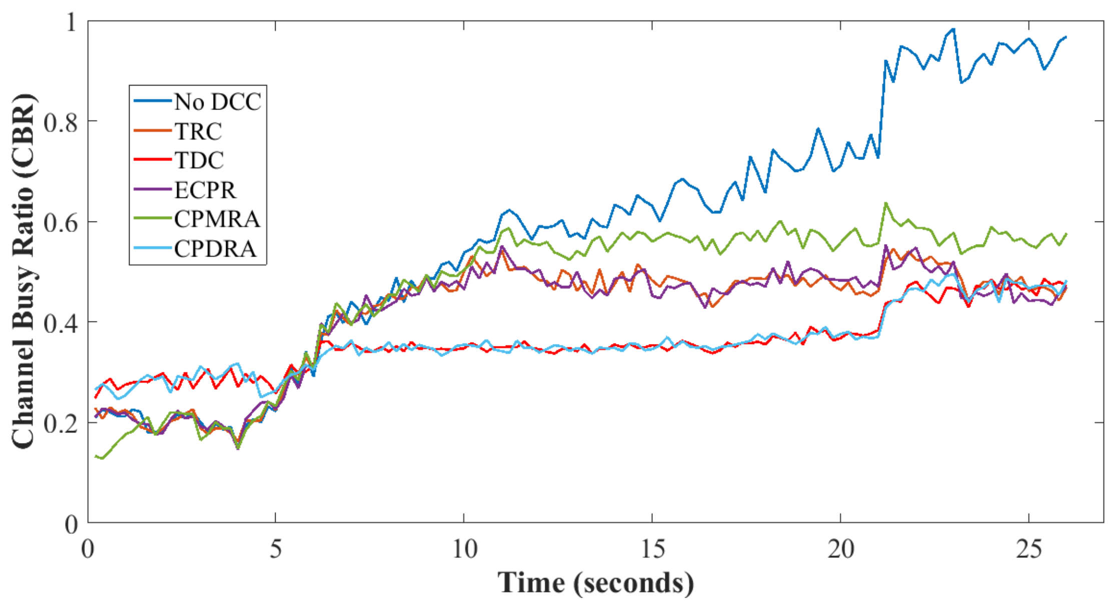


(a) CBR

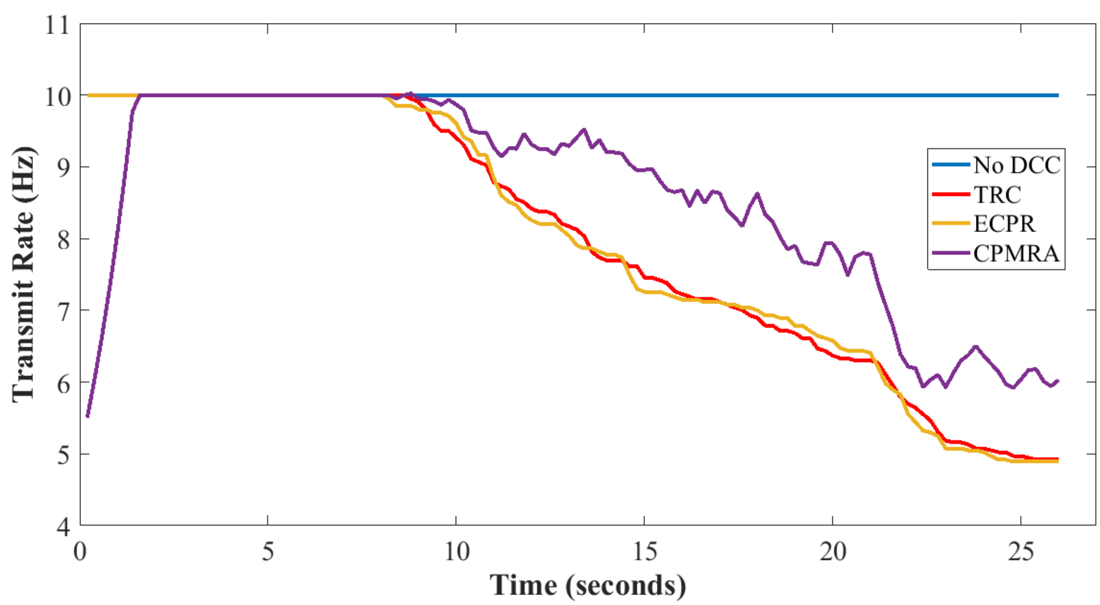
(b) Message Rate

Figure 4.4: CBR and Message Rate variations for transmit power=23 dBm and target awareness distance = 90m with 85% of target awareness

lated to data rate, data rate adaptation schemes have higher values of CBR compared to other mechanisms in relaxed state. As data rate starts changing with respect to current CBR value, number of available neighbors and feasible communication links



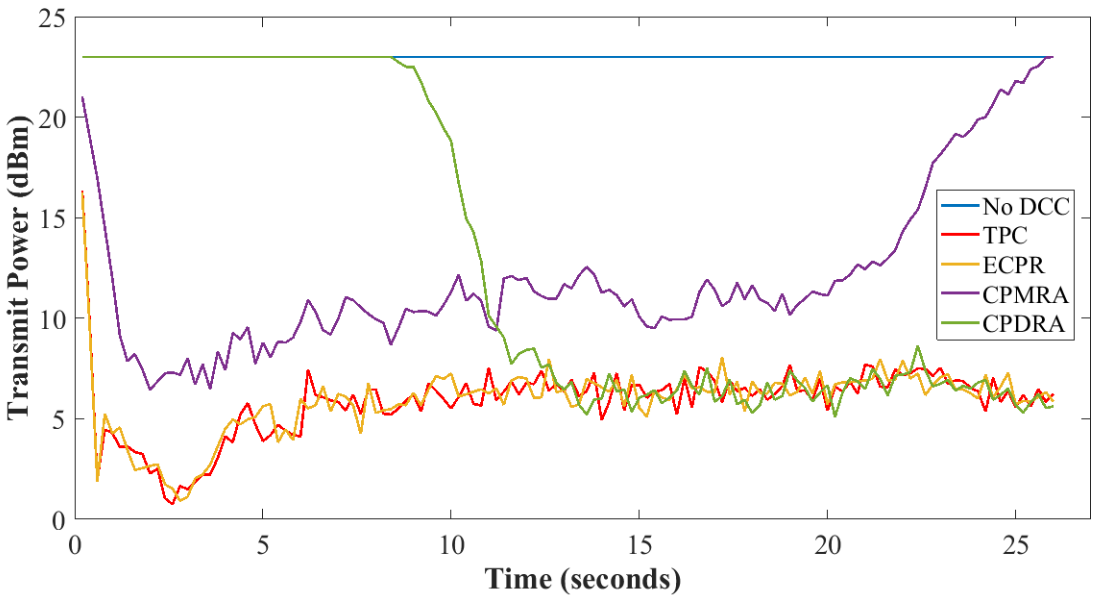
(a)



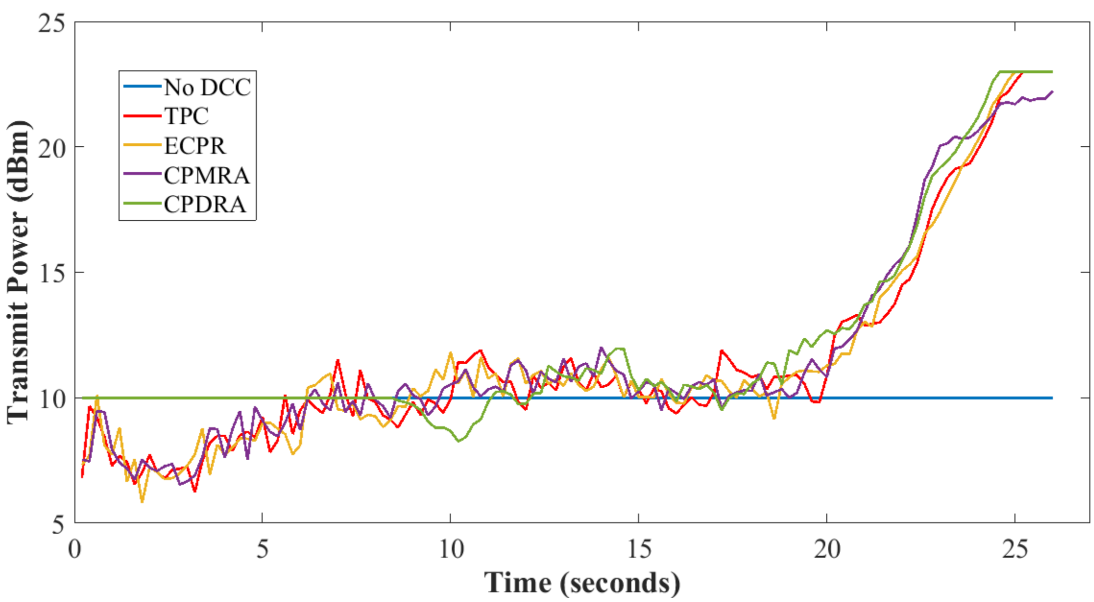
(b)

Figure 4.5: CBR and Message Rate variations for transmit power=10 dBm and target awareness distance = 150m with 85% of target awareness

start changing for every time step due to adapted values. This mechanism restricts CBR from crossing the threshold value specified by standard. The initial value of message rate in CPMRA mechanism is chosen to be 5 Hz and the adaptation of message



(a) Transmit power=23 dBm and target awareness distance = 90m



(b) Transmit power=10 dBm and target awareness distance = 150m

Figure 4.6: Variations in transmit power with 85% of target awareness

rate is shown in Fig. 4.4(b) and Fig. 4.5(b), variation in message rate is in the range $[1, 10]$. This variation in message rate keeps channel load in specified limits and proper channel utilization is achieved. Proposed CPMRA mechanism can be used for safety applications and CPDRA can be used for both safety and infotainment applications.

Fig. 4.6 shows transmit power adaptation applied to various DCC mechanisms. For initial transmit power of 23 dBm, the target awareness distance is chosen to be 90 m and for 10 dBm initial transmit power, it is chosen to be 150 m. This combination is selected to find equivalent amount of neighbors for both the cases as well as to avoid data loss due to collision. Transmit power plots show that depending on available channel load and awareness distance, transmit power is either increased or decreased to cover awareness area considered for ego vehicle. Power adaptation is applied to control the channel load and to avoid data loss due to increased load. For initial transmit power of 23 dBm, the decrease and increase in transmit power of CPMRA is because of variations in message rate, which also indicates more channel utilization by CPMRA. In CPDRA, the adaptation of transmit power starts once CBR crosses threshold value or change in number of neighbors.

4.3 Summary

In this chapter, we presented message rate and data rate adaptive DCC mechanisms combined with transmit power control. These mechanisms are implemented using two-state active design proposed by ETSI. In CPMRA, message rate is either decreased or increased depending on the channel load and value of convergence factor (α) is chosen based on the current DCC state. This variation in convergence parameter and message rate allows more channel utilization. Power adaptation algorithm is applied considering effect of neighbors as well as channel load. Different data rate values are chosen for different DCC states in CPDRA so that the channel congestion can be maintained in specified limits. These proposed mechanisms control channel congestion under realistic scenario generated using SUMO.

Chapter 5

CONCLUSION AND SCOPE FOR FUTURE WORK

Various safety requirements, investments by car manufacturing industry, public transport authority and growing area of applications brought intervehicle communication to the reality. MAC layer plays a critical role in fast and efficient delivery of safety related information for single hop communication. Providing comfort applications along with safety applications is also one of the aims of industry. Vehicular networks present some unique challenges because of all the constraints caused by mobility, road structure, communication environment, traffic rules and regulations and type of vehicles. These challenges are presented in chapter 2 of this thesis through extensive survey done at MAC layer and decentralized congestion control algorithms along with an insight of physical layer.

In this thesis, we developed I-MERLIN protocol to reduce number of broadcasts and improve amount of data transmitted over short encounters. Index coding is used in the design of I-MERLIN which encodes multiple files into single file of almost same size, hence multiple files can be transmitted in a single file. This saves number of transmissions at server which eventually saves transmission bandwidth. Only SCH interval is used for non-safety data transmission and CCH is reserved for safety applications. The performance of I-MERLIN is compared with available techniques and it is observed that, it performs better over these techniques. Results are obtained for different initial repository contents of clients and server, based on files received by all clients, final results are obtained. If RSUs are absent or rarely available, a clustering based approach is implemented for data exchange between vehicles. Clusters are formed between vehicles traveling in same direction so that cluster stability can be more due to minimum relative speed. The index coding helps in achieving more data exchange in cluster based approach. I-MERLIN can be used in low latency requirements with intermittent connectivity scenarios where bandwidth and resource allocation are focused.

The frequent exchange of safety and awareness messages leads to congestion, ETSI have proposed cross layered DCC mechanisms to overcome congestion by controlling parameters at physical or link layer. Transmit message rate adaptive (CPMRA) and data rate adaptive (CPDRA) decentralized congestion control mechanisms are presented which work combining with transmit power control algorithm. The two-state active design proposed by ETSI is used to implement these mechanisms. Performance is tested under real world scenario generated using SUMO. The message-rate adaptation along with power control in CPMRA helps in utilizing channel to more extent compared with other techniques by maintaining congestion in specified limits. Data-rate adaptation along with power control mechanism in CPDRA always keeps channel load below specified threshold and the power control mechanism works by considering environment variables and their effect on channel.

This area of VANETs is still growing and industry is focusing on various new outcomes to satisfy user demands. Internet of vehicles (IoV) is currently under development stage and it is an evolving area to focus on developing some applications considering network layer and transport layer issues. The connectivity at higher speed and providing in-vehicle Internet to users are some of the prime needs that can be explored further to achieve various demands of IoV system. The secure and reliable communication is one of the major concerns for IoV, focusing on protecting user data and maintaining privacy during communication. The use of blockchain technology in providing secure communication is one of current areas to focus on. The decentralized and distributive mechanism in blockchains can help to provide transparency by maintaining secrecy in user identity.

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Publications based on the thesis

Refereed International Journals/Conferences

1. Ashish Patil, N. Shekar V. Shet, "An index coded approach for reducing number of broadcasts in vehicular networks" *TENCON 2017 - 2017 IEEE Region 10 Conference, pp.1823 1827.* **DOI:** 10.1109/TENCON.2017.8228154.

2. Ashish Patil, N. Shekar V. Shet, "Improving Download Throughput by Saving the Transmission Bandwidth in Vehicular Networks" *Arabian Journal for Science and Engineering, Volume 44, Issue 4, pp 3967 3976.*
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3. Ashish Patil, N. Shekar V. Shet, "Clustering and cooperative data transfer in VANETs using index coding" *Int. J. Vehicle Information and Communication Systems, Vol. 3, No. 4, pp.355 367.*
DOI https://doi.org/10.1504/IJVICS.2018.095014.

4. Ashish Patil, N. Shekar V. Shet, "Challenges for Decentralized Congestion Control Mechanisms in Vehicular Ad Hoc Networks," *8th international Symposium on Embedded computing and system Design (ISED)*, Cochin, India, 2018, pp. 246-250. **DOI:** 10.1109/ISED.2018.8704020

5. Ashish Patil, Deeksha M., N. Shekar V. Shet, M. Kulkarni, "Transmit Data Rate Control based Decentralized Congestion Control Mechanism for VANETs" *International Conference on Data Science and Communication, Bangalore (IConDSC 2019), Bangalore, India, 2019, pp. 1-5.* ***DOI:*** *10.1109/IconDSC.2019.8816902..*

6. Ashish Patil, N. Shekar V. Shet, "Multistate Active Combined Power and Message/Data Rate Control Mechanisms for VANETs", *IET Networks*. (**Revision Submitted**).

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