Geometry-Predicting Communication Protocols for Car2X Applications

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Dedicated to My Parents

Abstract (English)

Vehicular Ad-hoc Networks (VANETs) have a broad range of applications that varies from safety appliances to comfort systems. To function properly, these applications require the services from efficient vehicular communication protocols. However, such networks hold unique characteristics induced by their application domain that necessitate their study from a substantially different perspective and with respect to other design goals than the prevailing paradigm for conventional Mobile Ad-hoc Networks (MANETs). The international standard IEEE 802.11p defines the low-layer protocols for VANETs aiming at support for Cooperative-Intelligent Transportation System (C-ITS) applications. Complementing this standard, it is argued that the Network layer and MAC layer are of crucial importance to reliability, availability and performance of VANET communication.

Addressing this issue, this work proposes a novel routing protocol called Traffic Aware Segment-based Routing (TASR), which is a multihop routing protocol specifically designed for the challenges of VANETs in urban environments. It accounts for VANET-specific characteristics in its design, such as their complex and dynamically changing topologies due to ubiquitous occlusions and reduced reach, high density and the agent mobility. TASR is a fully distributed protocol that does not require any fixed road infrastructure (roadside units, e.g. proxies). Its mechanism is designed to improve the success probability by dynamically estimating the multihop forwarding capabilities of road segments and the network connectivity among them. A novel metric called Estimated Connectivity Degree (ECD) is employed to estimate the connection quality of each candidate path between source and destination nodes. During the data packet forwarding phase, the next hop is selected based on maximizing the forwarding progress by utilizing a modified greedy geographic algorithm. TASR provides a solution to control the transmission overhead in each relaying node and to eliminate broadcasting in the whole transmission region. At the same time, TASR provides for the end-to-end robust communication meaning i) very high connection probability, ii) short network delay, iii) good bandwidth exploitation and iv) low error rate.

Reflecting the network dynamics inherent to urban VANETs and its consequential channel-access contention and time-window contention among the set of possible relay nodes, we have also addressed the medium access layer. To this end, a novel protocol called Cooperation and Network Coding based Medium Access Control (CNC-MAC) is proposed, extending IEEE

802.11 to improve the network throughput and the transmission reliability by allowing intermediate relay nodes to receive and merge the packets from the sender nodes.

A Contention Window (CW) adjustment scheme is designed that adapts to the node's velocity. Furthermore, as IEEE 1609.4 defines a MAC layer implementation for multichannel operations in VANETs, a Hybrid MAC (HyMAC) scheme has been proposed for emergency systems to improve the channel utilization of the Control Channel (CCH) and uniformly distribute the channel load over Service Channels (SCHs). In the proposed scheme, sub-networks dynamically change their operational mode from general to emergency node in order to increase probability for an urgent, time- and safety-critical messages to arrive in time.

Kurzzusammenfassung (Deutsch)

Verkehrsgerechte mobile Netzwerke (VANETs) haben ein breites Anwendungsgebiet, welches von Sicherheitsfunktionen bis hin zu Komfortfunktionen reicht. Um gemäß ihrer jeweiligen Spezifikationen arbeiten zu können, sind sie auf verkehrsgerechte Kommunikationsprotokolle angewiesen. Diese Netzwerke haben jedoch spezielle Eigenschaften aufgrund ihres Anwendungsgebiets. Es ist daher erforderlich, sie aus einer anderen Perspektive, mit Bezug zu anderen Design-Zielen als für konventionelle Mobile Ad-hoc Netzwerke (MANET) üblich, zu betrachten. Der internationale Standard IEEE 802.11p definiert diejeniegen grundlegenden Protokolle für VANETs, welche die Unterstützung der gewünschten Anwendungen in kooperierenden intelligenten Transportsystemen gewährleisten. Bei der Erweiterung dieses Standards spielen die Netzwerk- und MAC-Protokolle eine entscheidende Rolle für Zuverlässigkeit, Verfügbarkeit und Leistung der VANET-Kommunikation. Darauf bezogen stellt die vorliegende Arbeit mit Traffic Aware Segment-based Routing (TASR) ein neues Routing-Protokoll vor, welches als Multihop-Routing-Protokoll speziell für die Anforderungen von VANETs in urbanen Regionen ausgelegt ist. Es berücksichtigt VANET-spezifische Anforderungen, wie etwa komplexe und dynamische Topologien, welche sich etwa durch bewegliche Hindernisse für den Funkverkehr, eingeschränkte Funkreichweiten, eine hohe Teilnehmerdichte sowie die Mobilität der Agenten auszeichnen. TASR ist ein vollständig verteiltes Protokoll, welches nicht auf stationäre Straßeninfrastruktur angewiesen ist. Es wurde entworfen, um die Wahrscheinlichkeit für eine erfolgreiche Übertragung zu erhöhen, indem dyanmisch die Multihop-Weiterleitungsmöglichkeiten der Straßensegmente und deren Konnektivität eingeschätzt werden. Ein neues Maß, Estimated Connectivity Degree (ECD, der zu erwartende Konnektivitätsgrad), wird angewandt, um die Verbindungsqualität aller in Frage kommender Routen zwischen Quelle und Ziel einzuschätzen. Währen der Paketweiterleitung wird der nächste Abschnitt mithilfe von geographischen Greedy-Algorithmen auf der Route so ausgewählt, dass der Weiterleitungsfortschritt maximiert wird. TASR stellt eine Lösung bereit, den Overhead der Übertragung der weiterleitenden Knoten zu regeln, um die Verbreitung der Nachricht in der gesamten Region zu unterbinden. Gleichzeitig stellt TASR eine robuste Ende-zu-Ende Kommunikation bereit, was i) eine sehr hohe Verbindungswahrscheinlichkeit, ii) kurze Netzwerkverzögerungen, iii) eine gute Bandbreitenausnutzung, und iv) niedrige Fehlerraten gewährleistet. Aufgrund der Netzwerkdynamik, welche VANETs zugrunde liegt, und der daraus resul-

tierenden Kanalzugriffs- und Zeitfenster-Stauuungen unter den verfüg-
baren Weiterleitungsknoten, wird auch auf die mittlere Zugriffsschicht
Bezug genommen. Dahingehend wird ein Protokoll, das Cooperation
and Network Coding based Medium Access Control (CNC-MAC), einge-
führt, welches IEEE802.11p dahingehend erweitert, Netzwerkdurchsatz
und Übertragungszuverlässigkeit zu verbessern, indem zwischengeschal-
teten Knoten gewährt wird, eingehende Nachrichten zu Verknüpfen. Ein
Begrenzungsfenster-Anpassungsschema (CW) wird vorgestellt, welches
sich auf die Knotengeschwindigkeit einstellt. Außerdem, da im Rahmen des
IEEE 1609.4 Protokols für VANETs eine MAC-Schichten-Implementierung
für Mehrkanal-Operationen definiert ist, wird ein Hybrid-MAC-Schema
(HyMAC) für Notfallsysteme vorgeschlagen, welches die Kanalausnutzung
des Steuerungskanals verbessert. Es verteilt die Kanal-Last gleichförmig
über die Dienstkanäle. In dem vorgeschlagenen Schema wechseln Sub-
Netze dynamisch ihren Operationsmodus vom Allgemein- in den Notfall-
Modus, um die Wahrscheinlichkeit für die zeitnahe Übermittlung dringlicher
sicherheitskritischer Nachrichten zu erhöhen.

Part I
Presentation

Contents

1. Introduction

This thesis addresses urban traffic safety challenges by proposing innovative approaches in Cooperative-Intelligent Transportation System (C-ITS) for communication between vehicles. Traffic congestion and otherwise inefficient road transport is a central problem of our times. Numerous vehicles on the road being trapped in heavy traffic is a common phenomenon in day-to-day life, as is unnecessary and unsynchronized rides, etc. These phenomena not only waste time, energy and fuel but are polluting and cause fatigue and many other psychological problems as well. Furthermore, ensuring the safety of the lives of people has become major area of concern as vehicle density is on the rise and vehicles are now capable of traveling faster than ever before. The main objective of this research is to ensure reliable and efficient end-to-end communication between vehicles in high vehicular traffic density, especially urban traffic. Expensive sensors, radars, cameras and other sophisticated technologies are currently being integrated into vehicles to improve vehicle safety and driver-comfort during traveling. Their shared use by vehicle-to-X communication and non-local sensor fusion is considered to be the next large step in the development. Research in this area has gained considerable momentum over the last decade especially for communication-based applications which are based on Vehicle-to-Vehicle/Infrastructure (V2X) communications. These applications have attracted more attention from industries and governments in Europe (Network on Wheels Project, PReVENT Project) 2.4.1, United States (Vehicles Safety Communications Consortium) 2.4.2 and Japan (Internet ITS Consortium) 2.4.3 because of their unique potential to address vehicle safety, traffic congestion challenges at lower operational costs and monitoring of adherence to traffic rules and alerting the drivers about hazardous conditions.

Most modern vehicles of today already have intra-vehicular networks which allow seamless wireless connectivity between the vehicle's electronic control center and other electronic devices like smart phones, Global Positioning Systems (GPS), Bluetooth headsets and media players. But a network between vehicles is still not available. Vehicular Ad-hoc Networks (VANETs) are aimed towards doing just this. VANETs are emerging networks among vehicles and roadside infrastructure to serve applications which will improve safety on road networks and also provide content delivery on the move. VANETs are an extreme case of Mobile Ad-hoc Networks (MANETs) characterized by major variations in node density, network topology, environment and high speed mobility.

The IEEE has developed a system architecture called Wireless Access in Vehicular Environment (WAVE), which is a join of the standards IEEE 802.11p [Kenney, 2011] and IEEE 1609.x [IEE, 2016] to address the characteristics unique to VANETs and by providing WAVE. It is engineered to connect wireless devices attempting to communicate in a rapidly changing networking environment and in situations where data transmissions will have to take place in extremely short periods of time.

A key feature of traffic-safety systems is the coexisting and partially conflicting requirements on reliable and timely communications, which are due to the distributed control system. Timely and accurate data is needed to monitor and regulate the system. In spite of the ongoing academic and industrial research efforts on vehicular networks, many research challenges remain. Among them is the design of Medium Access Control (MAC) protocols that can make best use of Dedicated Short Range Communications (DSRC) [Kenney, 2011] as specified in (IEEE 802.11p-2006) multi-channel architecture. IEEE 802.11p is specifically designed to support vehicular network applications, which defines the general framework for multichannel management. The Physical layer (PHY) of DSRC has seven non-overlapping 10 MHz channels around 5.89 GHz, as shown in Figure 1.1. The center channel (178) is the Control Channel (CCH) and the remaining six channels are Service Channels (SCHs), including channels 172, 174, 176, 180, 182 and 184. CCH is a single channel which is reserved for short and high priority messages and system control messages. Each node in the VANET must monitor the CCH during time periods designated as CCH Intervals. The time period for an entire CCH Interval and SCH Interval is called Sync Interval as shown in Figure 1.2. Between control channel intervals, nodes may switch to participate on SCHs for applications such as file downloads. A WAVE announcement action frame is an announcement that is broadcast

on the CCH to inform nodes of available content on the SCHs. It is used to initiate a WAVE Basic Service Set (WBSS) to allow multiple nodes to communicate on an SCH. This thesis considers a system that operates in the United States.

Given that 802.11 is based on a radio model consisting of a single half-duplex transceiver, the DSRC radio can only communicate on one channel at a time. To use multiple channels, the radio must be dynamically switched between them as needed. This channel switching mechanism requires distributed coordination among the radios in the network, so that transmitters and their intended receivers are tuned to the same channel at the same time. In addition, VANETs are ideal to maintain a high quality of service in highly dynamic topologies, providing fast routing and security. These challenges motivate to test and apply new techniques, e.g., Cooperative Communication (CC) and Network Coding (NC), to improve the quality and enhance the overall communication experience.
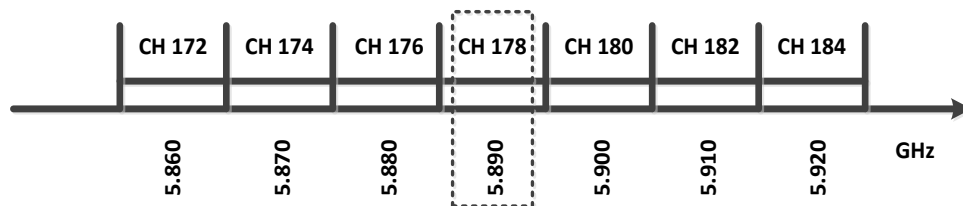
Figure 1.1: DSRC Channels. CH 178 is the CCH and others are SCHs
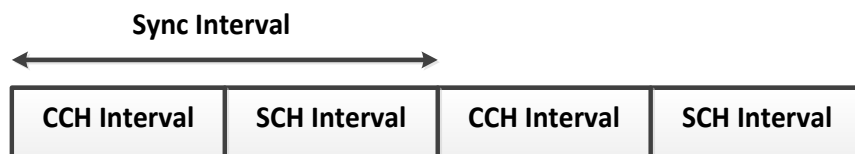
Figure 1.2: WAVE Sync Interval

With these premises in mind, comprehensible schemes are proposed in this thesis. The main problems were tackled, first with fundamental issues such as end-to-end communication and its reliability. Furthermore, on the bases upon it, methods to deal with reliable message delivery, emergency message arrival on time and cooperative networks in high traffic density and safety were proposed for urban scenarios. Initially, a novel VANET routing protocol is developed considering Inter Vehicle Communication (IVC) enabled vehicles, to allow the messages pass through in highly dense network. Then, cooperation and network coding approach is used, to increase the maximum throughput while minimizing the delay. Afterwards, as IEEE 1609.4 defines

a MAC layer implementation for multichannel operations in a VANET. In this sense, the urban traffic congestion problem by proposing algorithm for emergency situations is proposed, ensuring that networks change their modes from general (normal) to emergency mode. This increases the probability for messages to arrive in time. This scheme reduces the rate of transmission collisions in turn create latency and improves the reliability of message delivery in time. Moreover, safety concerns were always present, leading to new algorithms aiming to increase safe system operation. Finally, all system components were subjected to pass thorough simulation tests , to assess their correctness and appropriateness. For that purpose, different tools were used (OMNeT++, SUMO, Veins and time-driven C++ simulator).

1.1 Research Goals and Objectives

This research was conducted under the following specific goals:

- **Improve end-to-end communication.** Under dense vehicle traffic scenarios such as urban area, VANETs experience the broadcast storm problem which effects on end-to-end communication [Yu-Chee et al., 2002]. Although many valid approaches could be undertaken such as [Zhao and Cao, 2008] [Korkmaz et al., 2004] [Mo et al., 2006] [Li et al., 2014] etc. The problem occurs in basic data flooding techniques when data packet is disseminated in the network, intermediate node receives a data packet for further dissemination. An intermediate node then examine if it is the same data packet already received then it is discarded otherwise further disseminated. Since each node forwards data packets which causes inefficiency and delay that leads to redundancy which is basically depend on network node density, when a node receives multiple redundant data packets from all the neighboring nodes in the same radio region [Maglaras, 2014]. A reliable communication between V2V in urban environment has been chosen regarding their limitations. The main objective of this thesis is to solve this redundancy problem by evolving new routing protocol proposed by considering node density on each road segment in urban networks. So, in this thesis a new routing protocol is proposed as introduced in Chapter 4 considering node density on each road segment and aiming to improve urban networks.

- **Improve traffic safety.** In the literature of geographical forwarding algorithms such as, [Karp and Kung, 2000] [Lochert et al., 2003]

[Yong et al., 2007] [Luo et al., 2010a], The sender node select a next hop among neighboring nodes in such a way to minimize the forwarding progress, such as these neighbors are most often in the transmission range and closest to the destination. One major problem when operating under very high vehicle density in urban area is that vehicles evolving very close to each others radio region raises concerns with respect to safe operation. To address this problem, avoid the data congestion which creates overhead, a new data forwarding algorithm 4.6.2 is proposed.

- **Achieve high throughput by Network Cooperation (NC).** It is non-trivial to design an efficient reliable broadcast protocols in wireless networks. The fundamental challenges come from the unreliable nature of the wireless transmission links [Zamalloa and Krishnamachari, 2007], which is due to packet losses caused by channel fading and interfacing. In order to guarantee 100% Packet Delivery Ratio (PDR) with those unreliable links, some previous schemes used Automatic Repeat reQuest (ARQ) technique, which requires the receivers to provide explicit feedback's of the packet reception status to the source [Pagani and Rossi, 1997] [Sobeih et al., 2004]. However, this will cause "ACK implosion" problem which may incur a large amount of redundant transmissions. Other proposed schemes such as [Roger, 1998] [Jörg et al., 1997] [Luigi and Lorenzo, 1998] combine ARQ with Forward Error Correction (FEC) technique to reduce the transmission overhead while still guaranteeing 100% PDR. Yet, these techniqu es still consider the wireless link as point-to-point and neglect the fact that wireless medium is broadcast in nature. This leads to duplicate transmission at intermediate nodes, which are not enough for efficient transmissions. This is a very essential goal, since this network is highly mobile. These challenges motivate the testing and to employ new techniques, e.g., Cooperative Communications (CC) and network coding (NC) [Ahlswede et al., 2000], to improve the quality and enhance the overall communication experience. So, new MAC protocol 5.5 has been presented to enhance the network throughput and adjust the Contention Window (CW) 5.5.1 based on different scenarios.

- **Multi-channel scheduling for emergency situations.** To provide sufficient Quality of Service (QoS) for real-time safety applications, this objective would be achieved essentially by wirelessly broadcasting and warning messages between neighboring vehicles in order to

inform drivers timely in critical situations such as accidents. Previous studies focused on improving channel utilization and management. For instance, [Zhang et al., 2014a], [Zhang et al., 2014b] and [Bejaoui, 2014] increase channel throughput by adopting an adaptive CCHI depending on network density and a Time Division Multiple Access (TDMA) mechanism. Carrier Sense Multiple Access (CSMA) and Self-Organizing TDMA MAC (CS-TDMA) has been proposed by [Zhang et al., 2014a] combining CSMA and TDMA to improve the broadcast performance in VANETs but still these schemes are not fulfill satisfactory in terms of timely data delivery. So, in this aspect a new hybrid MAC scheme 6 were proposed where networks change their modes from general to emergency mode to increase the probability for a message to arrive in time.

To achieve the desire goals, it was necessary to promote the combination of related gathered knowledge in different fields such as traffic, communications and simulation. Since several problems had to be tackled, this work encompassed different fields of knowledge to achieve results that could enable new contributions for vehicular communication improvement.

1.2   Research Motivation and Problem Statements

VANET becomes a major research motivation for government agencies, vehicle manufacturers and academic institutions due to its wide variety of applications, high effectiveness and low cast development. However the successful deployment of VANET quires some pre-requisites in which the most important of it is how to establish adaptive and efficient routing paths between end users in a complex and dense urban communication scenarios. The benefits of VANETs will be limited without the available solution of this routing problem [Li, 2015]. After profound investigation and analysis the main challenges of VANETs routing system in urban scenarios are as follows.

1. **Accurate data packet routing obtainment.** Delivering data between source and destination in VANET environment requires robust and efficient routing protocol designed specially for this kind of network. As vehicle movement in VANET is restricted to bidirectional movements along the roads and streets, routing strategies that use geographical location information are practical and efficient for data delivery. Quality of Service (QoS) provides flexibility, scalability, efficiency,

adaptability, data reusability and maintainability [Chawla and Goyal, 2015]. The QoS of data packet routing metrics, such as end-to-end communication delay, data packet delivery ratio and connectivity probability play an important role in establishing available routing paths [Naja, 2013]. They offer characterization of the routes quality which is highly relevant to instantaneous and precise operational traffic information such as vehicle density, vehicle distribution and length of the road. B esides, routing QoS can directly affect the availability and efficiency of various applications, for example path availability notification to ambulance/fire brigade, emergent collision warning is require to be favorable, while providing available Voice over IP (VoIP) and Electronic-payment (E-payment) service to customers, reliable and robust routing paths with high packets delivery ratio are necessary [Hartenstein and Laberteaux, 2009]. Consequently, the QoS requirement for the network varies from the non-real-time to soft real-time where a timing failure might compromise service quality up to hard real-time where a timing failure might lead to a catastrophe [Maglaras, 2014]. Moreover, the spatial-temporal features of traffic conditions in VANETs are dynamic. For example, the spatial vehicle density can vary from very sparse to far dense, and the temporal vehicle density in one area can be variant depending on the time of the day. As a result, real-time and accurate routing QoS is very difficult to be estimated in VANET urban scenarios.

2. **Network Congestion.** Large-scale urban environments are characterized by a high concentration of vehicles in VANETs especially during rush hours, and their communication exchange can easily burden the wireless channel with high traffic loads and may result in significant impairment of the end-to-end data Packet Delivery Ratio (PDR) and transmission delay [Li, 2015]. Actually, these traffic loads include not only data packets but also a number of HELLO packets, which are used to broadcast geographic information among neighbor nodes. In addition, DSRC standard provides VANET communications with a bandwidth of only 75 MHz [Al-Sultan et al., 2014], and this spectrum is divided into 7 channels, one of which only owns a 10 MHz capacity. Obviously, higher traffic loads and limited bandwidth can easily induce network congestion and then exacerbate routing performance. Therefore, how to alleviate network congestion and reduce overhead in VANETs are very essential issues t hat are addressed in this thesis.

3. **Low QoS Performance.** Quality of Service (QoS) is the measure of a service offered by the network to the user. A service can be characterized by a set of requirements such as minimum bandwidth, maximum delay, maximum delay variance (jitter) and maximum packet loss rate [Kumar and Dave, 2010]. It is very important but difficult to keep the best QoS for packets forwarding especially in urban scenarios [Li, 2015]. The challenging tasks are that, information conceded by the network would be better delivered and additionally the network resources would be effectively utilized. The possible reasons are given as follows:

   - Urban environments are usually large-scale scenarios and the communication distance from a source to its destination may be considerably long. Furthermore, different kind of obstacle such as buildings, foliage etc make the communication more complex.

   - Global QoS of candidate routing paths are difficult to be known by a source vehicle, so routing exploration processes in large-scale networks are always based on local traffic information with random characteristics, which may result in the end-to-end routes including network-partitioned/congested road segments [Li, 2015].

   - Most traditional VANET routing protocols, such as [Perkins and Bhagwat, 1994] [Perkins and Royer, 1999] etc., lack of self-adaptation features and can not cope with topology changes available, which can disturb the process of forwarding packets.

   - Different communication pairs are usually absent of cooperation and do not make use of explored routing paths, so more routing exploration processes are implemented which may result in redundant overhead and higher transmission delay.

4. **Scalability, Reliability and Stability.** The scalability problem can be defined as the ability of a network to handle the addition of nodes or network size without being followed by a system failure or increasing the administrative complexity of the system [Neuman, 1994]. In vehicular context, guaranteeing a stable and scalable routing mechanism over VANETs is an important and necessary step toward the realization of effective vehicular communications. However, due to varying vehicle mobility and network topologies, routing paths are disrupted frequently and it is very difficult to ensure their stability. In addition, end-to-end node-based or intersection-based source-driven

routing paths are not available in large-size urban environments as they can not handle the scalability issue [Kosch et al., 2006] [Li, 2015]. Furthermore, there are more issues such as lack of real time traffic and alternate route information, lack of readily available transit information t o increase ridership.

5. **Heterogeneity Conveyed Data Packets** VANETs are supposed to provide a wide variety of applications ranging from safety to infotainment applications [Delot et al., 2009] [Lee et al., 2007b] [Kitani et al., 2008] [Wischhof et al., 2005]. Road safety applications usually require low transmission delay and high reliability whereas resource utilization, packet loss and fairness are the common performance measures for infotainment applications. Besides, different QoS metrics maybe counterproductive to each other in some communication scenarios, for example, dense vehicles are advantageous to the improvement of connectivity but may increase packet loss ratio because of channel congestion and interference. By means of different traffic information, the best QoS routing selection with multiple QoS thresholds to satisfy with heterogeneous applications should be considered [Li, 2015].

1.3   Key Contributions and Benefits

The key contributions and their benefits of this research work are listed as follows;

- **Routing Protocol.** Due to the high mobility and dynamic nature of vehicular networks, great challenges exist for real time efficient data delivery. One major challenge is to provide for robust communication in spite of high dynamic topologies and the presence of shielding obstacles without installing extra relay infrastructure. Inter-Vehicle Communication (IVC) is the keystone where the traffic-density information and density estimation schemes are a valuable asset to approach this challenge. In this light Traffic Aware Segment-based Routing (TASR) [Khan and Fränzle, 2015] [Khan et al., 2018] is proposed, aims at finding a robust route that has minimum hop count and transmission delay while achieving a high Packet Delivery Ratio (PDR) and overcoming the adverse effects of high mobility. To this end, we develop an segment based algorithm to obtain real-time vehicle density information. A connected road segment is a segment between two adjacent intersections with enough vehicular traffic to ensure network

connectivity. Recent studies have been followed in multihop routing in VANETs 3.1 which have shown that geographic routing with the help of GPS and digital maps ensures low end-to-end delay, low control overhead, and high end-to end PDR. Vehicles exchange packets using short-range wireless interfaces such as IEEE 802.11 and DSRC. All these protocols assume that an efficient location management service is available to provide the source node with the destination location for routing. The proposed protocol adopts related techniques to provide a robust route from source to destination. The basic operations of TASR comprises two alternating phases: The first phase deals with selection of a segment by leveraging real time vehicular traffic information to calculate the Expected Connectivity Degree (ECD) of different segment. The best path can be selected by employing new metric (ECD) that takes in to account vehicles densities and the expected connectivity on each segment, which consider the connectivity of nodes and data delivery ratio for transmitting packets, while data forwarding takes place in the second phase as follows in next section.

- **Data Forwarding Algorithm.**

  A new modified geographical greedy forwarding technique is used to transmit data packets from source to destination. During the packet forwarding phase, the next hop is chosen in such a way as to maximize the forwarding progress and always select node closest geographically to the destination. This process continues until the packet reaches the destination. Therefore, to successfully choose next forwarding hops, it is vital for each en-route node to keep a precise neighbor list. However, due to the broadcasting a large overhead may be occurred. A new solution is proposed to control the extra overhead in data transmission.

- **Cooperation and Network Coding Algorithm.** The main motivation of this protocol named Cooperation and Network Coding (CNC) MAC 5.5 [Khan et al., 2015] lies on exploiting the advantages of both Cooperative Communication (CC) and Network Coding (NC). The cooperation during the operation of the protocol results in a distributed cooperative Automatic Repeat reQuest (ARQ) scheme, while NC techniques are used in order to improve the performance of the system. CNC-MAC allows to enhance throughput up to 80% to 90% by minimizing the number of transmission. Furthermore, the proposed protocol performs better under high mobility and significantly reduces

the number of packet loss, thus saving a considerable amount of time and resources.

- **Contention Window Adjustment.** The contribution in this part is how to adjust the Contention Window (CW) according to the vehicle contact time with other vehicle. When a vehicle inquires access to the channel and the channel is busy, then it creates a CW. Fast vehicles are prioritized in this concept as they get out of range sooner than slow vehicles. They rely more on a timely access to the channel than slow vehicles. We expect increased fairness over a number of the observation intervals, in terms of how long the CW should be active by the relay nodes on the estimated time that they spend in the active transmission range.

- **Channel Scheduling.** A novel scheme named Hybrid MAC (HyMAC) [Khan et al., 2017] tailored for broadcasting emergency messages in urban VANETs. The challenge of urban VANET is to cope with frequent obstructions blocking radio transmissions. HyMAC is based on a real-time channel access mechanism exploiting the Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) techniques exploiting real-time channel switching (considering CSMA and TDMA for the channel switching simultaneously). HyMAC is designed such that CSMA and TDMA switch dynamically in emergency situations, taking into account density and dynamics of vehicles, allowing for optimizing the utilization of the CCH leading to increased throughput and reduced latency.

  CNC-MAC and HyMAC protocols focuses on meeting the non-safety and safety requirements respectively. CNC-MAC assume that when an erroneous data packets received by the receiver due to an obstacles in between or with high speed by a vehicle, the receiver then request for cooperation from nearby relay nodes. CNC-MAC not considering the timely manner communication but keep high throughput in account. HyMAC scheme is based on a real-time message distribution when a vehicle detects an emergency event, it will broadcast an emergency message to nearby vehicles. For example, if a vehicle detects dangerous stuff such as a sharp object fallen from a construction truck on the road or car collision in front, it will notify other vehicles behind to avoid the object. In these cases, emergency messages need to be delivered to each node nearby with almost no delays. A vehicle that detects an emergency event usually only needs to broadcast its emergency

message to other vehicles in a short range, such as a range of several hundred meters. A single hop delivery may therefore be adequate for this type of application, which makes routing for emergency packets less relevant. In such a case, MAC becomes the most critical segment in the delivery process of an emergency packet.

- **Simulation Testbed** The most important task after an idea presentation is implementing the application. It was very mandatory to decide the VANET testbed and analyze the different features and capabilities that it provided to develop, furthermore simulating and test the application. Simulations have advantages that can hardly be replaced by testbed experiments. In simulations, different network scenarios can be constructed and amended according to the requirements. Using simulations the data can be easily collected. More importantly, a large scale network scenario can be model which would be very costly in real. The simulator had to be capable of simulating the vehicular networks as well as provide control to the application to mimic the behaviour of a human driving the vehicle. OMNeT++ and C++ tools are used for implementations.

1.4   Thesis Synopsis

The remaining of this thesis is structured as follows:

Chapter 2 reviews the VANETs background and related work in detail. The characteristics and practical applications of VANETs are presented as well. VANETs main technical issues, challenges and additionally some related VANETs typical projects from Europe, United States and Japan are discussed.

Chapter 3 investigates in greater detail the most relevant VANET routing protocols of five different categories (topology based, geographic based, cluster based, geocast based and broadcast based) are introduced. The selected data packets forwarding algorithms are also presented in this chapter.

Chapter 4 presents the proposed routing protocol named Traffic Aware Segment-based Routing (TASR), especially designed for city environment that takes the advantages of the road topologies to improve the end-to-end communication performance. TASR protocol uses real-time vehicular traffic information to create road-based paths between end-points. Furthermore, these selection is based on Next-to-Next (N2N) segment selection. A new metric called Estimated Connectivity Degree (ECD) used for the segment

selection. Afterwards, a modified data forwarding algorithm is used used for data forwarding. Simulation were conducted which shows that TASR outperform with its competitor protocols.

Chapter 5 introduces a new MAC protocol named Cooperative and Network Coding MAC (CNC-MAC). The proposed protocol presents how to cover the transmission failure issues utilizing network coding technique. Furthermore, Contention Window (CW) adjustment scheme is proposed according to the nodes velocity. CNC-MAC protocol exploits the advantages of cooperative communication and network coding techniques to outperform the CARQ-MAC protocol as selected.

Chapter 6 introduces Hybrid MAC (HyMAC) scheme for VANETs that exploits the advantages of multiple channel access. The proposed scheme is tailored for emergency communication in urban environments to improve the channel utilization of the Control Channel (CCH) and uniformly distribute the channel load on hijacked Service Channels (SCHs). The performance evaluation results show that the proposed hybrid scheme outperforms its stat-of the-art competitors such as VeMAC and IEEE 802.11p (WAVE).

The final chapter 7 recounts and summarizes the main findings and conclusions presents in the work. Also suggested the possible future research initiatives.

2. Background and Related Work

This chapter introduces the basic characteristics and applications of Vehicular Ad-hoc Networks (VANETs), followed by an overview of their technical issues and associated projects. In addition, a number of appropriate selected routing protocols and selected data packet forwarding algorithms for VANETs are also presented.

Before proceeding to VANETs, it is mandatory to give a brief introduction of Mobile Ad-hoc Networks (MANETs). A MANET is a self-organized network which consists of devices that can dynamically be set up and can operate without any centralized control by pre-existing infrastructure [Corson and Macker, 1999]. The devices in MANET communicate with each other within the same radio region utilizing the wireless medium. Each device in MANET acts as a data terminal or computing device such as laptops, mobile phones, wearable computers and Personal Data Assistants (PDAs). MANETs have several salient characteristics such as their dynamically changing network topology, pertinent bandwidth constraints, tight energy constraints and limited physical security. VANETs are one of the special sub-class of MANETs that shares some common characteristics as detailed in the following section.

2.1   Characteristics of VANETs

The advancement in mobile communication technology and the current trends in ad-hoc networks allow different deployment architectures for vehicular networks in highways, urban and rural environments to support many applications with different quality of service requirements. The goal of a VANET architecture (as shown in Figure. 2.1) is to allow the communication among vehicles and between vehicles and fixed roadside equipments [da Cunha et al., 2014]. In VANETs the three possible communications techniques are;

Figure 2.1: Traditional architecture for Vehicular Ad-hoc Networks (VANETs).

1. **Vehicle-to-Vehicle (V2V) communication:** The direct vehicular communication can be established by making use of the On-Board Units (OBU) installed in vehicles instead of depending on the fixed infrastructure. Using internet-based transmit and receive will probably remain the method of choice for communications as long as the ratio of WiFi-enabled vehicles remain low. However, the ubiquity of WiFi-enabled vehicles will ease the way for ad-hoc networks of moving vehicles [Nzouonta-Domgang, 2009]. The advantage here is the addition of a distinct, high bandwidth network to the existing infrastructure network. The major drawback is that these networks require a new set of protocols. [Riva et al., 2007] [Riva et al., 2008].

2. **Vehicle-to-Infrastructure (V2I) communication:** This technique enable vehicles to communicate with the roadside infrastructure through equipped Road Side Units (RSUs). V2I communication is mainly used for information and data gathering applications. Two essential variants can be found in the literature: the access points could be installed specifically for the purpose of providing internet access to vehicles or the latter could make use of open 802.11 WiFi access points encountered opportunistically along city streets [Nzouonta-Domgang, 2009].

   The benefits of this connection method is that vehicles use higher data rate internet (e.g. 11Mbps) as compared with cellular-based technologies (e.g. Long-Term Evolution (LTE), Global System for Mobile (GSM), 2G and 3G etc.). The reason behind is that, still this is unclear that how LTE networks will perform in very congested scenarios and under certain operator roaming conditions. For example, messages for traffic management are particularly relevant to highly congested urban scenarios [802,]. GSM considered to be another cellular system standards that provides a data rate of a maximum of 9.6 Kpbs and is characterized as Second Generation (2G). For multimedia packets transmission, a high data rate is required which led to the development of the Third Generation (3G). This cellular technology can provide a data rate up to 2Mbps [Olariu and Weigle, 2009]. The drawbacks include the cost for acquiring reasonable coverage by installing access points along the roads. Additionally, in the case where open access points are used, the access point owner's consent would legally be required before such a service is deployed [Car,].

3. **Hybrid communication:** Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) combine and make an hybrid communication networks. In such networks vehicles can communicate with the roadside infrastructure either in a single hop or multihop fashion. It also enables long distance connection to the Internet or among vehicles that are far away from each other. Advantages of this method is that high probability of connectivity and maximum bandwidth could be achieved by cooperating with each other. The major disadvantage is that this method is economically expensive.

VANETs form a specific class which inherits several characteristics from general MANETs. Both of them are self-organizing networks and com-

posed of mobile nodes. However, VANETs still are in possession of many particular features as follows:

1. **Sufficient power:** Power scarcity in VANETs is less serious as compared with MANETs. Modern communication devices installed in vehicles are supported by stronger batteries providing extensive storage and recharge-ability, which are beneficial for effective communication and freedom in making routing decisions and other computational tasks.

2. **Effective capabilities:** There is relatively much space in vehicles, so various devices owning significant computing and communication power can be installed. Further, sensing capacities can be installed such as advance antenna technology and GPS, which make vehicles capable of powerful functions and high computational abilities [da Cunha et al., 2014].

3. **Predictable mobility:** Unlike MANETs in which mobile nodes move rather randomly, the movements of vehicles specially in urban VANETs are partially controlled by the defined street topologies, traffic light and regulations. Consequently, future position of a vehicle can be predicted based on roadway information such as street digital map and destination location.

4. **Large scale application scenarios:** VANETs are always laid out in highway or urban environments which constitute large networks and include a high number of communication mobile nodes, while MANETs are often studied in limited-size environments (walking human or mobile device).

5. **Quick network topology changes:** In VANETs vehicles are moving with high and different speed, and they are also changing their directions constantly, so network topologies are very dynamic and communication links are not stable, which may lead to network partitions.

2.2   VANETs Applications and Use Cases

Cooperative-Intelligent Transportation System (C-ITS) can support the practical implementation of a wide range of VANETs applications. By defining and characterizing these applications allow to identify the communication requirements for the different C-ITS technologies and communication

protocols that have to comply to support them. According to the typical characteristics of VANETs in Section 2.1, the ITS Technical Committee of the European Telecommunications Standards Institute (ETSI TC ITS) has summarize and identified a set of reference applications and use cases for the standardization and future deployment of C-ITS [Tec, 2009]. Figure 2.2 shows that the selected applications can be categorized into three main different groups as follows: road safety applications, traffic efficiency and management applications, and infotainment applications. For each of the reported applications classes, some possible use cases are indicated as well.

2.2.1 Road Safety Applications

Road safety applications are classified as either cooperative awareness or road hazard warning applications. Cooperative awareness applications are designed to detect dangerous situations through the cooperative wireless communications between the vehicles. For example, the authors listed in [Alshaer and Horlait, 2005] [Mangharam et al., 2007] [Lee et al., 2010a] [Zhuang et al., 2011] provide road safety applications such as avoiding vehicle collisions to decrease crash and death ratio, and emergency vehicles (fire brigades, ambulance, police) calls for assistance. In these applications the traffic related information must be transferred quickly, otherwise there will be high risk in delaying related information. Road hazard warning applications are in charge of the instantaneous environmental notification of dangerous events upon their occurrence on the road network [Rondinone, 2013]. The essential for this case is reliability, all vehicles close to hazard should be alerted. These applications include lane change assistance, stationary vehicle on the road, collision warning and so on.For example, when there is hazard (e.g. accident) on one lane (left/right), safety messages including related accident information are broadcasted through V2V/V2I wireless communications to control the traffic flow properly. The road traffic will then change to another lane (left/right) or directly leave that lane at the exit, so this scheme can avoid serious traffic congestion and further traffic accidents [Li, 2015].

2.2.2 Traffic Efficiency and Management Applications

Applications for traffic efficiency and management focus on improving the traffic flow, supplying faster routes, giving adaptive traffic lights and providing real-time and localized traffic information. In this category, most of the applications require a high availability of information, since drivers have to use the obtained information to make decisions. These applications
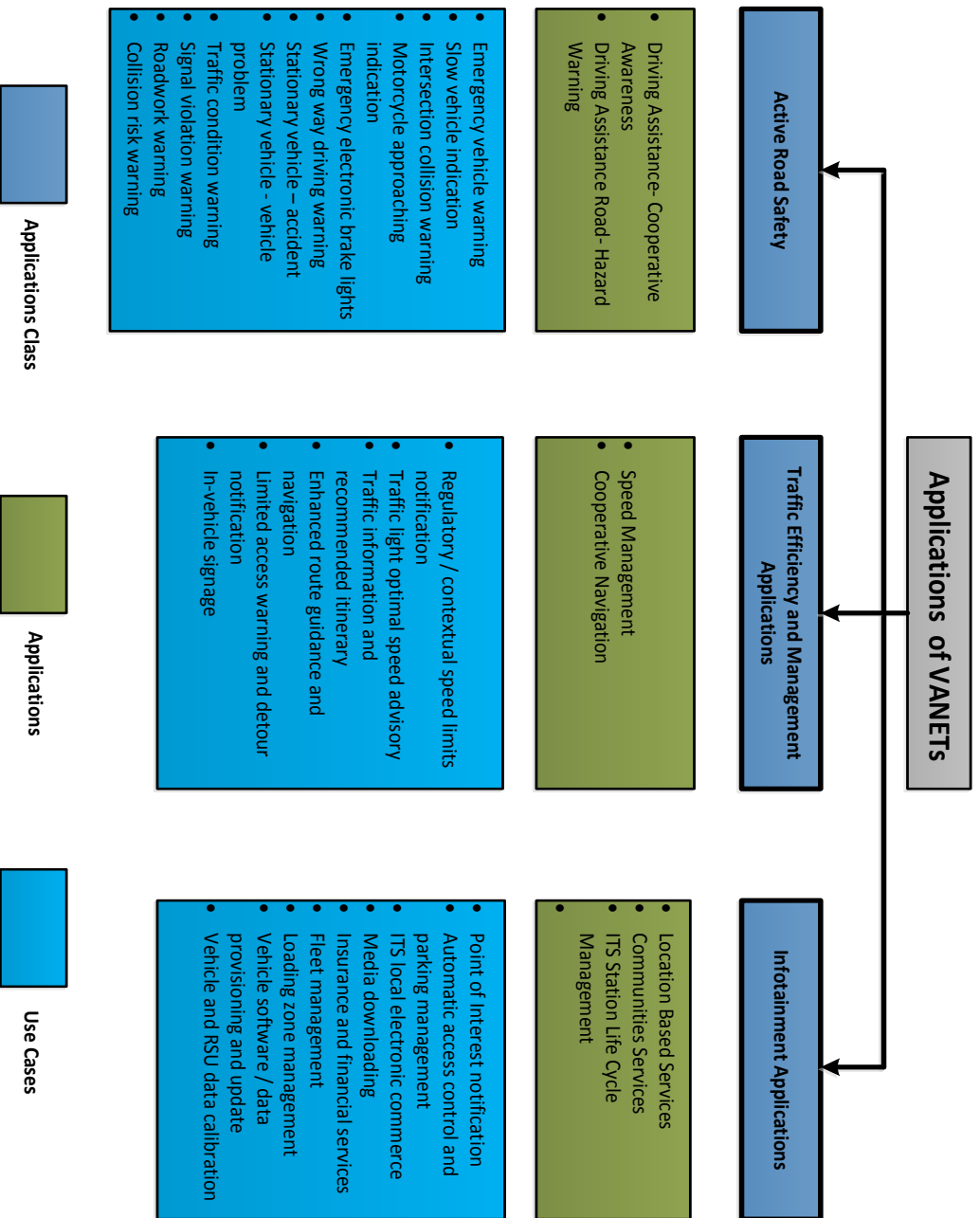
Figure 2.2: Applications of vehicular ad-hoc networks. [Tec, 2009] [Rondinone, 2013]

mainly consist of speed management and cooperative navigation systems. In this context, a typical example of speed management systems [Lui and Ozguner, 2003] [Ni et al., 2010], which aim to assist the driver in managing the speed of a vehicle for smooth driving and to avoid unnecessary stopping. Besides, this system provides regulatory/contextual speed limit notification and green light best speed advisory to related drivers. A cooperative navigation system [Tatchikou et al., 2005] [Seiler et al., 2004] [Li and Wang, 2006] is utilized to increase the traffic efficiency by managing the navigation of vehicles through V2V and V2I communications. In this use case, a vehicle can be inform by approaching vehicle through wireless communication about abnormal situations like traffic congestion in specific areas of the road network.

2.2.3 Infotainment Applications

Infotainment applications [Delot et al., 2009] [Lee et al., 2007b] [Kitani et al., 2008] [Wischhof et al., 2005] are referred to as non-safety fields of application which are beneficial to improve drivers and passengers comfort levels and make trips more pleasant. Each of the identified applications and use cases has distinct requirements in terms of communication settings and performance requirements [Wai et al., 2011]. For example,vehicles should be able to broadcast information at a minimum frequency which receive information with maximum latency and ensure a given radio coverage, etc. [Rondinone, 2013]. Based on curiosity, the typical essentials to use these applications are reliability, availability and connectivity, so as to provide the information in the right moment and right time that the drivers need. In this case, an intersection warning application require s broadcasting messages at a minimum frequency of 10Hz and receive messages with a maximum latency of 10ms. On the other hand, traffic information application can initially tolerate latencies of 500ms and work with a broadcasting frequency of 1HZ. These differences are due to the need to increase the robustness and reliability of active safety applications [Rondinone, 2013]. Some of the major infotainment applications of, e.g., Apple's Carplay system [Huynh, 2016] are illustrated in Figure 2.3. It is a system that integrates the iPhone apps with the vehicle's digital systems and allows the driver to use basically all the iPhone's functionality (such as playing the music, finding the favorable shops, making phone calls, reading text messages) without actually touching it, which makes the driver control the devices more easily and conveniently [Li, 2015]. In addition, there are many more smart-phone independent applications which can provide weather forecast

report, location of the nearest accessible restaurant/hotel and play on-line games etc. to the drivers and passengers.

Figure 2.3: Comport applications of Vehicular Ad-hoc Networks by Carplay.

2.3 Technical Issues in VANETs

According to above descriptions in Section 2.1, VANETs are expected to be more and more used in our daily lives and helpful to the promotion of Cooperative-Intelligent Transportation Systems (C-ITS) and smart cities. However, many factors which have a critical impact on VANET objectives have to be taken into consideration, so it is vital to specify the key issues that still need to be solved. The key problems from the technical perspectives are given as follows.

1. **Signal fading:** Obstacles located between two communication vehicles are one of the challenges that can prevent the signal from reaching its destination, increasing the fading in the wireless channel and reducing the transmission efficiency. These obstacles may be other vehicles, foliage and buildings distributed along roads especially in urban scenarios [Hartenstein and Laberteaux, 2008a]. In addition, condensing humidity and raining can also be originators of signal damping.

2. **Bandwidth limitations:** VANETs lack a central coordinator regulating V2V/V2I communications, doing bandwidth management and controling contention by operational restriction. In addition, the range of frequency bandwidth for VANET applications is limited and only 75 MHz are allocated in the Dedicated Short Range Communications (DSRC), so channel congestion can occur easily especially in high density environments. Obviously, it thus is necessary to efficiently optimize bandwidth utilization [Fazio et al., 2011], which has an important impact on QoS based routing. For example, if the wireless channel is busy, a vehicle requiring packet forwarding has to wait for some time for the idle statement of this channel, so that the transmission delay of packet increases particularly in high traffic-load scenarios.

3. **Connectivity:** Due to the high vehicle mobility and rapid changes of topology, network fragmentation take place frequently in VANETs [Viriyasitavat et al., 2011], so it is better to elongate the time duration of link communication as long as necessary. This task can be accomplished by increasing transmission power, but at the expense of serious interferences and throughput degradation. Therefore, connectivity is considered to be an important issue in VANETs. Although many studies in MANETs [Blum et al., 2004] [Artimy et al., 2004] have focused on solving this problem, it still occupies a wide portion of the efforts gathered towards the development of VANETs.

4. **Small effective diameter:** Because of the small effective network diameter of VANETs, the QoS of the link between two nodes may degraded and the wireless link maintenance of complete global network topology is impracticable for a node. For example, on a crowded highway the number of vehicles contending for access the wirless medium is large. For instance, in agridlocked four lane highway with vehicles placed 15m apart, approximately 300 or more vehicles contend for channel access (e.g. 600m diameter/(15m between vehicles * 4lanes * 2 directions) = 320 vehicles). Because a large number of vehicles are contending for access to the medium, it is necessary to vary the size of the contention window to reduce the likelihood of a collision. Vehicles can also benefit from the opposing situation where the contention window is decreased to account for light traffic [Blum et al., 2004]. The restricted effective diameter results in problems that existing routing algorithms available in MANETs can not be directly used in VANETs [Fazio et al., 2011].

5. **Security and privacy:** It is very important to guarantee security and privacy in VANETs. In case of security challenges, such as selfish vehicles attempting to clear up the way ahead or to mess up the way behind with false traffic information, the result may be serious accidents and even loss of lives. The other issue is to protect the vehicle owner's privacy. It is very easy to acquire vehicle information such as speed, status, trajectories from data sharing in and open properties of VANETs. By mining this vehicle information, malicious observers can make inferences about a driver's personality, living habits and social relationships, which could be exloitet by, e.g., trading in underground markets and may bring threats to drivers.

6. **Routing protocol:** Because of complex vehicle movements and highly varying connection topology, designing an efficient routing protocol that can deliver a packet successfully within lowest delay is considered to be a critical challenge in VANETs.

   This research thesis mainly focuses on the problems related to data communication in the network and MAC layers.

2.4 Vehicular Networking Projects

Motivated by the development of new value-added applications, several consortia (e.g., automotive industries, highway control authorities, toll service providers and safety organizations) have engaged in a large number of VANET projects. These collaborations have come to actual implementations, which are an essential and necessary part of the verification of VANET systems. An account of major VANETs projects carried out in European Union, USA and Japan is presented below.

2.4.1 European Union

The aim of many European projects are provide the ability to the people that use European roads to benefit from improved traffic safety, minimize the traffic congestion and more environmentally friendly driving. This can be realized by providing standardized and common communication means between vehicles driving on these roads as well as between vehicles and road infrastructure.

1. **FleetNet-Internet on the Road:** FleetNet [Fle, 2003] was a pioneering research project that operated from 2000-2003. This project was initiated by Daimler, automotive suppliers and research institutes.
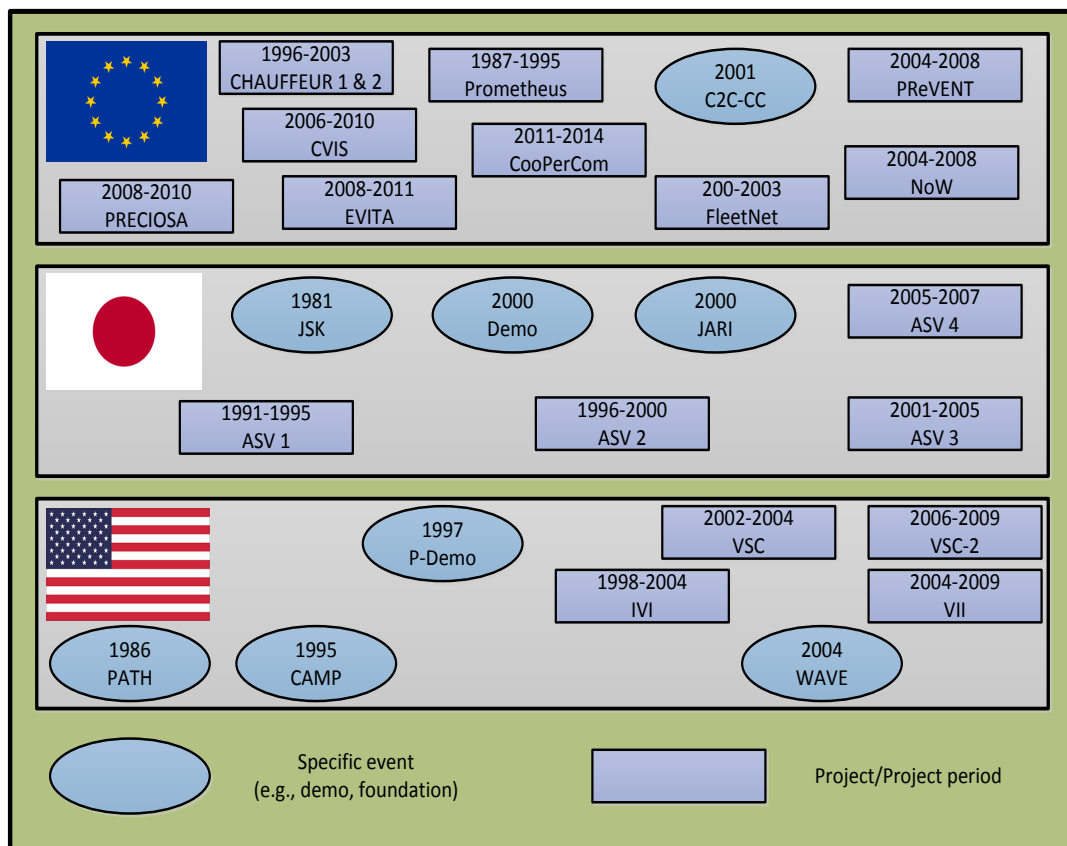
Figure 2.4: A non-exhaustive overview of pioneering activities and milestones that show the evolution of the topic of VANET research around the globe. In addition to that, various projects are currently funded in the EU, Japan, the United States, and other parts of the world.

FleetNet was partially funded by the German Ministry of Education and Research (BMBF). This project can be regarded as an initial feasibility study for direct communication among cars, i.e., Car-to-Car (C2C) communication. FleeNet considered three different classes of application such as cooperative driver-assistance for road safety, local floating car data applications and user communication and information services. The project investigated different radio technologies such as IEEE 802.11, UTRA-TDD and data transmission utilizing radar communications and later on it focused on IEEE 802.11. As one of its main results, the project developed a prototype of a C2C communication platform as a proof-of-concept.

2. **NoW-Network on Wheels:** The NoW (Network on Wheels) project [NoW,] was the successor of the FleetNet project running from 2004-

2008. NoW was initiated by the major German manufacturers and partially funded by the German Ministry of Education and Research (BMBF). Objectives of this project were to leverage results of the Fleet-Net project and to develop an open communication platform for road safety, traffic efficiency, and infotainment applications. Besides technical aspects, NoW also analyzed strategies for market introduction and supported the Car-2-Car Communication (C2C-C) Consortium which is an industry consortium promoting an open European standard for CAR-2-X communication.

A particular characteristics of the NoW system is the integration of applications for road safety and infotainment in a single system. Clearly, safety and infotainment applications have very different requirements and characteristics. Infotainment applications typically establish sessions and exchange unicast data packets over a long period of time. On the other hand, safety applications typically broadcast messages to neighboring nodes. The project distinguished between two different types of safety messages. Periodic status information, such as beacons or heartbeats, achieve cooperative awareness among vehicles. Event-driven safety messages are non-periodic messages, triggered by the detection of an abnormal condition or imminent danger. Periodic messages are broadcast to the neighbor nodes and not distributed via multihop forwarding by the network protocol. In contrast, event-driven messages are distributed via multihop forwarding to a certain geographical area specified by the source node.

3. **PReVENT:** PReVENT [PRe, 2008] was an integrated project of Research and Development (R&D) co-funded by the European Commission to increase road safety by investigating preventive safety technologies and applications. Preventive safety system make use of information, communication, sensors and positioning technologies to help drivers avoid or mitigate an accident. PReVENT operated from 2004 to 2008 and consists of 13 sub-projects. Two sub-projects of PReVENT investigated research issues related to vehicular networking such as Wireless Local Danger Warning (WILLWARN) and Intersection Safety (INTERSAFE). The other sub-projects of PReVENT conduct research in other areas such as sensor technologies, radar technologies, laser technologies, positioning technologies, digital map technologies, data fusion techniques, control and decision systems, human machine interfaces and strategies for market introduction. The

sub-projects WILLWARN and INTERSAFE are briefly summarized below.

4. **Car-2-Car Communication Consortium:** The CAR-2-CAR Communication Consortium (C2C-CC) [C2C, 2016] is a nonprofit, industry driven organization initiated by European vehicle manufacturers and supported by equipment suppliers, research organizations and other partners. The C2C-CC is dedicated to the objective of further increasing road traffic safety and efficiency by means of cooperative Intelligent Transport Systems (C-ITS) with Vehicle-to-Vehicle Communication (V2V) supported by Vehicle-to-Infrastructure Communication (V2I). It supports the creation of European standards for communicating vehicles spanning all brands. As a key contributor the C2C-CC works in close cooperation with the European and international standardization organizations. In cooperation with infrastructure stakeholders the C2C-CC promotes the joint deployment of cooperative ITS. To improve mobility on the roads it has adopted the ITS Action Plan indicating 24 concrete measures in 6 priority areas with target dates spanning from 2009 to 2014. The initiated iMobility Forum and a number of R&D programs including large scale field operational tests contribute to the reduction of road fatalities, to improve the efficiency and to reduce the environmental impact of road traffic in all areas including smart cities. The C-ITS will provide new active safety measures to further enhance the existing passive safety systems preventing or mitigating traffic accidents. As energy consumption and emissions need to be reduced and road traffic needs to exploit road capacities, new foresighted driving measures are required to support sustainability, e.g. green driving.

5. **Cooperative Perception and Communication in Vehicular Technologies (CooPerCom):** CooPerCom [Coo, 2010] project is considering two objectives, as follows;

   Objective 1: How to improve the reliability and robustness of the vehicular embedded systems and sensors which are becoming more ubiquitous, numerous and complex over time. As the number of sensors and systems increases, the challenges of ensuring sufficient reliability and safety are becoming overwhelming. In addition, vehicular environment is highly dynamic and thus requires a high level of connectivity, which in turn requires reliability and robustness as well.

Objective 2: This project is to explore and develop intelligent signal and information processing tools so as to make use of multiple vehicles presence and Inter-Vehicles Communication (IVC) capabilities. It additionally aims at collecting source information for individual data chunks validation and to assess the level of uncertainty which exploit potential redundancies. These information are beneficial to mitigate risk of unexpected failures and optimize reliability as well as robustness.

6. **Cooperative Vehicles and Infrastructure Systems (CVIS):** CVIS [CVI, 2010] is an R&D integrated project co-funded by the European Commission is to run from 2006 to 2010. CVIS's high-level goal is to control the traffic system by continuous communication and cooperative services between V2V and V2I to increase road safety and traffic efficiency. CVIS also aims to provide greater precision in vehicle location and supply the generation of more dynamic and accurate mapping using recent location referencing methods. In addition, it addresses the systems for cooperative traffic and network monitoring in both vehicle and roadside infrastructure along with the ability to detect potentially dangerous incidents. To this end, CVIS provide the following four enabling services [Olariu and Weigle, 2009]:

   (a) **COMM:** Provides a network architecture that allows transparent and continuous C2X communication.

   (b) **POMA:** Provides positioning, map services and location referencing services.

   (c) **COMO:** Provides cooperative monitoring services and allow both local and central data fusion.

   (d) **FOAM:** Provides an open end-to-end framework to enable a communication link between vehicles and infrastructure.

7. **E-safety Vehicle Intrusion Protected Applications (EVITA):** EVITA [EVI, 2012] is a project co-funded by the European Commission to address safety threats by preventing unauthorized manipulation of on-board systems, so as to successfully prevent the intrusion into the in-vehicular systems and the transmission of corrupted data to the outside. Actually, EVITA complements SEVECOM and NoW which focus on communication protection. The main contributions of EVITA are given as follows:

(a) The overall security requirements are defined through identifying the necessary industrial use cases and compiling substantial scenarios of possible threats.

(b) A corresponding trust model is proposed.

(c) A secure on-board architecture and protocol are specified.

Thus, EVITA provides a basis for the secure deployment of electronic safety aids based on V2V and V2I communication.

2.4.2   United States

Industrial, governmental and university research organizations efforts have created significant opportunities in different projects such as VSC, PATH etc. Several vehicular networking protocol standards are used in these projects such as WAVE protocol standard that are standardized by the IEEE in the IEEE 802.11p and IEEE 1609 protocol set. In 1991 the United States Congress via Intermodal Surface Transportation Efficiency Act (ISTEA) requested the creation of the Intelligent Vehicle highway Systems (IHVS) program. The Goals of this program were to increase traffic safety and efficiency while reduce the pollution. The U.S. Department of Transportation (DOT) got the responsibility of the IHVS program with the cooperation of Intelligent Transportation Society of America (ITSA). All the current research and innovation which is associated with DOT is administrated and managed by Research and Innovative Technology Administration (RITA). In 1996 a framework named National Intelligent Transportation System Architecture (NITSA) has been developed where IHVS services could be also planned and integrated which is now a days known as Intelligent Transportation System (ITS). NITSA supported the use of wireless communication for ITS service where. Automated Toll Collection (ATC) is the first ITS service [Karagiannis et al., 2011].

1. **Vehicle Safety Communication (VSC and VSC-A):**

   The VSC project was a 2.5 year project which is started in May 2002. VSC consortium members were BMW, Daimler-Chrysler, Ford, GM, Nissan, Toyota and VW. The aim of VSC is to facilitate the advancement of vehicle safety through communications technologies based on the following objectives:

   (a) Identify and evaluate the safety benefits of vehicle safety applications enabled or enhanced by communication.

(b) Assess the communication requirements, including V2V and V2I modes.

(c) Contribute to DSRC standards and ensure they effectively support safety.

(d) Develop next generation DSRC testing system.

(e) Test and evaluate DSRC communication functionalists for potential vehicle safety implementation.

VSC is to support the development of traffic safety applications, especially in the fields of cooperative forwarding of collision warnings, curve speed warnings, stop sign movement assistance assistant, traffic signal violation warning, lane change warning and so on.

In order to deepen the research done in VSC, a new project called Vehicle Safety Communication-Application (VSC-A) [Ahmed-Zaid et al., 2011] was a three years project (December 2006-December 2009), and its objectives are as follows:

(a) Assess how previously identified critical safety scenarios can be improved by means of Dedicated Short Range Communication (DSRC) technology along with positioning systems.

(b) Determine the minimum system requirements and related performance parameters for vehicle safety applications operating in conjunction with the DSRC system.

(c) To implement communication models deployment for vehicle safety systems.

The technologies were tested in real world at Orchard Lake and Ten Mile Road Intersection (Farmington, MI 48336, USA). One Road Side Unit (RSU) was placed in the intersection for send and receive the messages and also synchronized traffic signal controller. The RSU was able to transmit 500 byte messages including signal state and timing every 100 msec. On the other hand On-Board Unit (OBU) send and receive messages of 200 byte including actual V2V common message set every 100 msec.

2. **Vehicle Infrastructure Integration (VII):** The VII [Kandarpa et al., 2009] Consortium supplies coordination to key automobile manufacturers (such as Ford, General Motors, Daimler-Chrysler, etc.), the state transportation departments and professional associations. The test environment of VII covers 50 square kilometers near Detroit, USA,

and it is used to test a variety of prototype VII applications, which are composed of:

(a) Warning drivers of unsafe conditions and imminent collisions.

(b) Supplying real-time information to system operators concerning congestion, forecast information and other potentially hazardous incidents.

(c) Providing operators with real-time information on corridor capacity such as warning drivers if they are about to run off the road or speed around a curve too fast.

To some extent, results along these lines have been achieved in trials performed around the globe, making use of GPS, mobile phone signals, and vehicle registration plates. Today's equipment is designed for data acquisition and functions such as enforcement and tolling, not for returning data to vehicles or motorists for response. As well as there are numerous limitations to the development of VII. A common misconception is that the biggest challenge to VII technology is the computing power that can be fitted inside a vehicle.

3. **California Partners for Advanced Transit and Highways (PATH):** The project of PATH [Chan et al., 2012] was implemented by University of California, in cooperation with several state and federal administrations. The PATH project mainly focused on policy and behavior research, transportation safety, traffic operation research such as traffic managements and traveler information systems and additionally also provide technologies to improve transmission solutions for dependent drivers.

2.4.3 Japan

In July 1996, five related government bodies jointly finalized a "Comprehensive Plan for ITS in Japan" [ITS, b] [ITS, a].

These government bodies are the National Police Agency (NPA), Ministry of International Trade and Industry (MITI), Ministry of Transport, Ministry of Posts and Telecommunications (MPT) and Ministry of Construction.

The above listed government bodies recognized the need to develop a design that could respond to changes in social needs and development in technology in the future. In August 1999, they jointly released a first draft of the "System Architecture for ITS". This purpose to release this draft

was to collect different opinion from industrial and academic sectors and to openly address the information worldwide. Finally, in 1999 the "System Architecture of ITS" has been finalized.

Major projects in Intelligent Transportation System (ITS) area are presented in this section. Some facts and results regarding to these projects are as follows: By May 2001, approximately 20 million vehicles were equipped with Electronic Toll Collection On-Board Units (ETC OBUs), In particular, as of June 5, 2008 in the expressways nationwide, 74.1% of all vehicles used ETC and on the metropolitan Expressways, 81.1% of all vehicles used ETC. In comparison, in March 2006, the annual distribution of Vehicle to Information and Communication System (VICS) on-board units was approximately 3 million and in November 2007, the aggregate distribution of VICS on-board units surpassed 20 million [Karagiannis et al., 2011].

1. **Advanced Safety Vehicle Program (ASV):** ASV [Hiramatsu et al., 2007] is composed of a series of ongoing development projects (ASV-1, ASV-2, ASV-3 and ASV-4) covering various trial phases and supported by Japanese Ministry of Transport, automobile manufacturers (Honda, Mitsubishi, Suzuki and Toyota in particular) as well as academic and research organizations. The trials focus on two aspects including active and passive safety. In the case of active safety, some related systems (such as systems for drowsiness warning, vision enhancement, navigation, automatic collision avoidance and lane departure) are designed and tested to assist in the prevention of a crash. In the case of passive safety, several systems for impact absorption, occupant protection, pedestrian protection and door lock sensing are designed to protect occupants during a crash.

2. **Public-Private Cooperation Program ITS-Safety 2010:** ITS-Safety 2010 [ITS, c] is a project that performs on-road verification tests to present current ITS technologies and verify the effectiveness of ITS services installed along public roads. As the result of ITS-Safety 2010, two V2I cooperative systems have been actualized in Japan from 2011:

    (a) ITS spot on highway service to provide wide area traffic information, hazard warning, road condition ahead, etc.

    (b) DSSS (Driving Safety Support Systems) on ordinary roads to satisfy with stop sign recognition enhancement, crossing collision and rear end collision prevention support.

3. **Electronic Toll Collection (ETC) System:** ETC [Lida et al.,] also known as a nonstop toll collection system is an R&D project for V2I collaboration system that offers driving support services enabled by high-throughput bidirectional communication through ITS spots installed alongside the highways. ETC enables the automatic, cashless payment of road tolls as vehicles drive through toll gates,m by means of wireless communicators between toll gate antennas and terminals mounted in vehicles. This system is able to yield the reduction of traffic volume in specific locations, the decrease of time periods prevention of accidents because of the smooth traffic fluency and the mitigation of the deterioration of roadway structures. As a result, the limited resource of road networks can be used more efficiently and intelligently and for an extended period of time. In addition, ETC provides a wide variety of services.

    (a) Congestion avoidance support: vehicle drivers can select the optimum route when entering into the metropolitan area based on traffic information and they can also determine expected travel time for each route by using a car navigation device equipped with ETC.

    (b) Support under disaster: the system provides assistance information when disasters occur, indicating type of disasters and their impacts.

    (c) Discount service: The toll road company offers several discount service to the ETC-use driver such as specified area discount and time of day discount. In order to increase the number of ETC users, discount service was started.

    (d) Convenience for the driver: Before the ETC system, it was inconvenient for the driver to own the left-hand drive car because most of the toll collections devices were set on the right side. Thanks to the ETC system that they make it convenient.

According to the above descriptions, vehicular networking standardization and research activities in USA, Europe and Japan have been investigated and promoted for the development of relevant technologies in VANETs, so as to improve traffic safety, reduce road congestion and advance traffic efficiency. Besides, these projects reveal that different design objectives induced by specific applications require diverse QoS guarantees from the communication infrastructures, such as delay, robustness, scalability, etc., all of which are still challenging in the field of VANETs.

Road safety applications are classified as either cooperative awareness or road hazard warning applications. Cooperative awareness applications are designed to detect dangerous situations through the cooperative wireless communications between the vehicles. For example, the authors in [Alshaer and Horlait, 2005] [Mangharam et al., 2007] [Lee et al., 2010a] [Zhuang et al., 2011] provide road safety applications such as avoiding vehicle collisions to decrease crash and death ratio, and emergency vehicles (fire brigades, ambulance, police) calls for assistance. In these applications the traffic related information must be transferred quickly, otherwise there will be high risk in delaying related information. Road hazard warning applications are in charge of the instantaneous environmental notification of dangerous events upon their occurrence on the road network [Rondinone, 2013]. The essential for this case is reliability, all vehicles close to hazard should be alerted. These applications include lane change assistance, stationary vehicle on the road, collision warning and so on.For example, when there is hazard (e.g. accident) on one lane (left/right), safety messages including related accident information are broadcasted through V2V/V2I wireless communications to control the traffic flow properly. The road traffic will then change to another lane (left/right) or directly leave that lane at the exit, so this scheme can avoid serious traffic congestion and further traffic accidents [Li, 2015]. In these applications the traffic related information must be transferred quickly, otherwise there will be high risk in delaying related information. Road hazard warning applications are in charge of the instantaneous environmental notification of dangerous events upon their occurrence on the road network [Rondinone, 2013]. The essential for this case is reliability, all vehicles close to hazard should be alerted. These applications include lane change assistance, stationary vehicle on the road, collision warning and so on. For example, when there is hazard (e.g. accident) on one lane (left/right), safety messages including related accident information are broadcasted through V2V/V2I wireless communications to control the traffic flow properly. The road traffic will then change to another lane (left/right) or directly leave that lane at the exit, so this scheme can avoid serious traffic congestion and further traffic accidents [Li, 2015].

2.5 Chapter Summary

The background and related works of VANETs are introduced in this chapter. Firstly, the characteristics and practical applications of VANETs are presented, then the existing challenges and main technical issues in VANETs

are started. Besides that, some popular and typical VANETs related projects implemented in European Union, United States and Japan were introduced to trace the progress of vehicular networks research.

3. Evaluation of Existing VANETs Routing Approaches

3.1 Routing Protocols in VANETs

Over the past decade, a large number of routing protocols have been proposed and surveyed for VANETs, e.g. [Al-Sultan et al., 2014] [Altayeb and Mahgoub, 2013] [Hartenstein and Laberteaux, 2008a] [Paul et al., 2011] [Zeadally et al., 2012] [Lee et al., 2010b], where the main goal of these routing protocols is to provide the best path through multihop wireless communications. In this section, the most representative literature in the area of vehicular routing is presented. This involves a brief discussion of the major groups of protocols, namely topology based, geographic based, cluster based, geocast based and broadcast based. Thus the VANET routing protocols are divided into different categories according to their core concept as shown in Figure 3.1. Some of the most popular protocols are described below.

3.1.1 Topology Based Routing Protocols

Topology based routing protocols utilize link information that exists in the network to perform packet forwarding. Routing tables, maintained at each node, are used to store the link information of all other nodes in
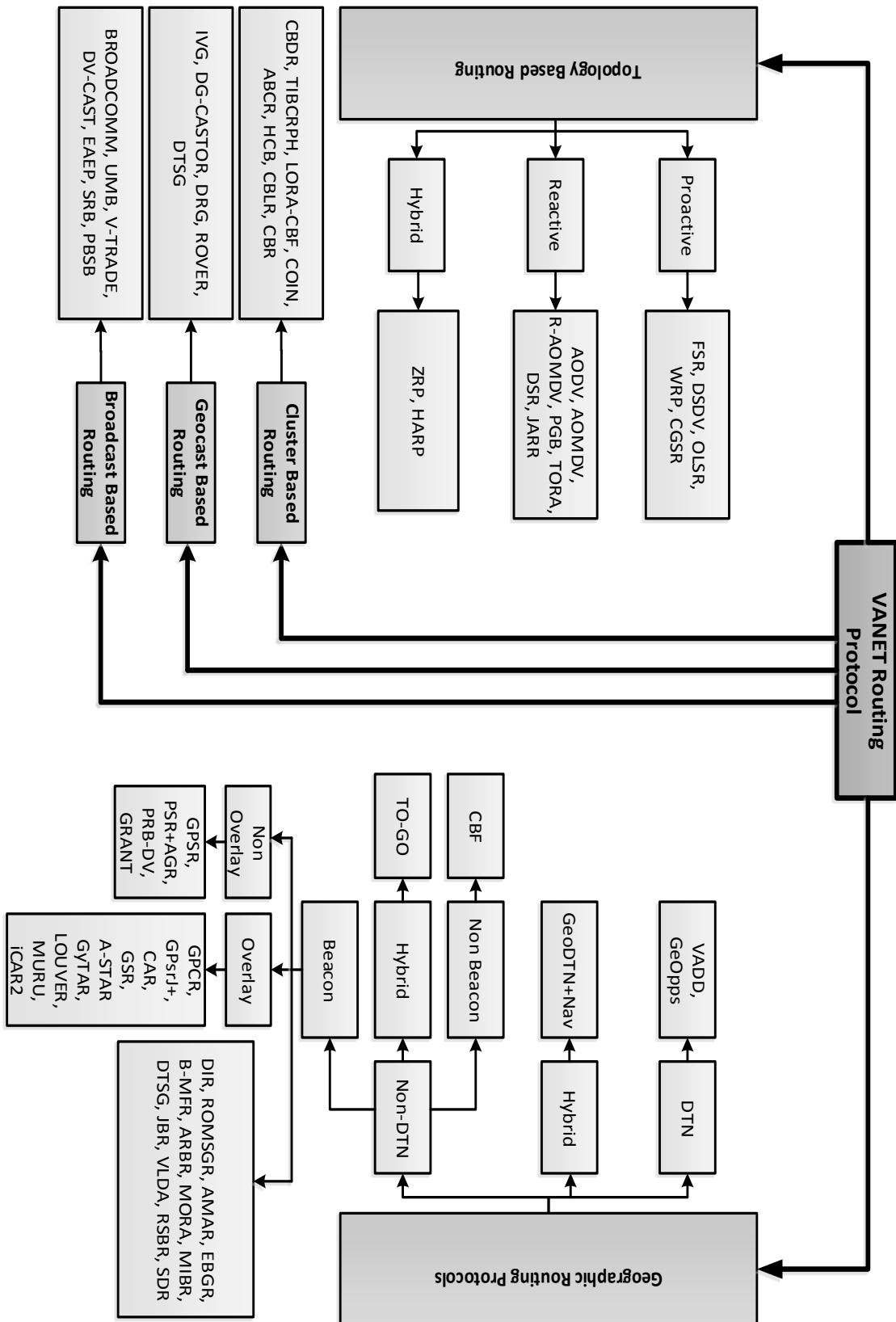
Figure 3.1: Types of VANET routing protocols.

the prevailing topology. As the nodes in VANETs are constantly moving, routing tables must be maintained and updated frequently. Based on this update of the routing table, topology based routing protocols can be further divided into proactive (table-driven), reactive (on-demand) and hybrid [Al-Sultan et al., 2014].

3.1.1.1 Reactive Routing

Reactive (on-demand) routing opens a route only when it is necessary for a node to communicate with another node. It maintains only the routes that are currently in use, thereby reducing the burden on the network. Reactive routing typically has a route discovery phase where query packets are flooded into the network in search of a path. The phase completes when a route is found.

Ad-hoc On-demand Distance Vector (AODV) [Perkins and Royer, 1999], in when a route is needed to send some data packets, the source node broadcasts a request message. When the destination receives the request, it sends back a reply message through a temporary path to the source node. The source node then establishes connection using the route that has the least number of hops. The unused entries of the routing tables are discarded after some time. If a link fails, then a routing error message is passed back to the source, and the process starts again.

Ad-hoc On-demand Multipath Distance Vector (AOMDV) [Marina and Das, 2001] and On-demand Multipath Distance Vector with Retransmission counts metric (R-AOMDV) [Chen et al., 2009] are both routing protocols extending AODV. AOMDV also takes advantage of control messages like AODV uses, but just adds extra fields to reduce the overhead occurring during the process of discovering multiple paths. Here, AOMDV keeps all available paths in the routing table, then the source selects the first established route as the preferred one. AOMDV outperforms AODV in reducing route discovery retransmission while improving robustness and decreasing transmission end-to-end delay. In the R-AOMDV routing protocol, a source node sends a route discovery packet when it does not own a path to its destination.

R-AOMDV protocol makes use of a routing metric that combines hop count and transmission counts at MAC layer by taking quality of intermediate links and delay reduction into consideration. This protocol has been shown to deliver better performance than AODV, especially in sparse and dense urban vehicular networks. The route discovery process employed in R-AOMDV is similar to that of AOMDV. It relies on two control packets:

Route Request (RREQ) and Route Reply (RREP). The intermediate first hop nodes in RREQ and RREP packets are used to distinguish between multiple paths from source to destination. To measure quality of entire path, it adds two additional fields to RREP packets: (1) the Maximum Retransmission Count (MRC) that is measured in MAC layer and (2) the total hop count that is measured in network layer. When RREP is passed back to the source, each intermediate node compares its retransmission count with the MRC and replaces it if its retransmission count with the MRC and replaces if its retransmission count value is greater than the current MRC. Thus, when RREP packet arrives at the source, the source can identify which path contains maximum MRC. As in AOMDV, a source node in R-AOMDV initiates the route discovery process whenever it can not find a path to the required destination in its route table [Jarupan and Ekici, 2011].

Temporally Ordered Routing Algorithm (TORA) [Park and Corson, 1997] is a distributed routing protocol using multihop routes and is designed to reduce the communication overhead related to adapting to frequent network changes. TORA constructs a directed graph which consider the source node as the tree root. Packets should be forwarded from higher nodes to lower nodes in the tree. Once a node broadcasts a packet to a particular destination, its neighbor needs to broadcast a route reply to check if it has a downward link to the destination, if not, it just drops the packet. TORA ensures multipath loop free routing since the packet always flows downward to the destination and do not flow upward back to the sending node. The advantages of TORA are that it offers a route to every node in the network if it is reachable to all. and reduces the broadcasting of control messages. However, it causes routing overhead in maintaining routes to all network nodes, especially in highly dynamic networks such as VANETs.

Dynamic Source Routing (DSR) [Johnson et al., 2001], the source node indicates the sequence of intermediate nodes contained on the routing path in the data packet's header file as it uses source routing. The query packet copies in its header the identities (IDs) of the intermediate nodes that it has traversed. The destination node then retrieves the entire path from the received query packet and utilize it to send reply back to the source node. If the destination node replies with multiple routes then the source node stores all the paths and utilizes them when the current route fails.

Preferred Group Broadcasting (PGB) [Naumov et al., 2006]is a broadcasting mechanism that aims: (1) to reduce control messages overhead associated

with AODV's route discovery by eliminating redundant transmissions and (2) to obtain stable routes with the ability of auto-correction. While a minimization of a routing load is very desirable in any of the possible ad-hoc scenarios, the stability of a chosen route becomes especially important in an environment where fast moving vehicles are used as wireless hosts. In a broadcasting-based route discovery process, no special criteria are used when choosing the intermediate nodes. Thus it can easily be the case that two nodes in a path are very close to each other, or vice-versa are separated by a distance close to the maximum communication range. Neither of the cases is desirable. Short distances between hops imply a high number of hops in the path. On the other hand, when a hop length is close to a maximum coverage range, the connection can be easily lost if one of the nodes moves out of the range, or slightly changed interference jams the weak signal. Moreover, poor connection quality leads to throughput degradation, due to an increased number of errors. If an adaptive data-rate is used, then a high bit error rate forces the data-rate to decrease and this step may lead to a bottleneck problem in the current node. PGB classifies each node that receives a broadcast packet (e.g. Route Request (RREQ)) into one of the three groups based on the sensed signal level:

- Preferred Group (PG) - the preferred set of nodes;

- IN group - nodes with a signal stronger than in PG;

- OUT group - nodes with a signal weaker than in PG.

The disadvantages of PGB protocol is that, there exists a problem on low vehicular density area such as highway. Furthermore, in PGB one node is allowed to broadcast and since the PG is not necessarily the one that makes the most progress towards the destination, route discovery might take longer than before. Another disadvantage is tat broadcast can discontinue if the group is found to be empty as discussed that PGB works worse in sparse network (highway). Packet duplication can occur when two nodes in the PG broadcast at the same time. It also creates the same overhead like DSR protocol when deal with the broadcast duplication as to add predecessors into the original packets [Wafta, 2010].

Junction-based Adaptive Reactive Routing (JARR) [C.A.T.H.Tee and Lee, 2010] is designed to suit multihop data routing in a city environment. A data packet has to traverse through many paths and junctions from its source to destination. Every path is considered to be multi-lane and two-way roads.

Sparse and dense network conditions are also considered to suit actual traffic conditions. Vehicles are able to communicate using wireless devices up to the range of 250 meters. GPS or other positioning determining methods are used to obtain position information of vehicles. A location service which is used to obtain the position information of the destination node is assumed to be available. This is to ease the simulation process because the main concern is the packet forwarding process and the reliability of data delivery. Packets are routed from a junction to an optimal path and then continue to be forwarded until they reach another junction. At this next junction, routing decisions are made to choose the next optimal path to take. When on a path, next best hops for the packets are also chosen reactively. This reactive multihop routing process will continue until the packet reaches its destination. The paths as well as next hops are chosen based on highest calculated weighted scores. The algorithms that calculate the scores have to take into account the vehicle's velocity, direction of travel, current position and vehicle density information. Depending on location of the vehicles and network conditions, these factors will have different weight on the algorithms. With varying algorithm in different conditions, a packet has to switch between different forwarding modes. The different modes relate to the current location of a vehicle and affect the algorithm accordingly. This is to ensure routing decisions can be made on-the-fly in different network conditions. At the start of a transmission, a packet could be on a path or a junction. The shortest path from the source to the destination is calculated in the beginning to get a general direction of where a packet should be forwarded. The packet then switches to its specific mode depending on its current location. In all the modes, information of neighboring nodes are being gathered periodically. These information facilitate in making routing decisions and estimating the density of vehicles on a path.

3.1.1.2 Proactive Routing

Proactive routing protocols are also acknowledge as table-driven routing protocols. Proactive routing carries the distinct feature that the routing information, such as the next forwarding hop is maintained in the background regardless of actual communication requests. Therefore, control packets (HELLO packets) are constantly broadcast among the nodes to maintain paths connecting between any pair of nodes. Some paths of the link states between any pair of nodes are used which show that these paths are still alive and some of them are never used which can be also used. A routing data table is then established within a node such that each entry in the data table indicates the next hop towards a certain destination. The

advantage of the proactive routing protocols is that there is no explicit route discovery upon start up of a communication since route to the destination is maintained in the background and always available upon look-up. The protocols advantage of providing low latency for real-time applications, however, comes at the price of spending a significant part of the available bandwidth on the background activity of node and path discovery, especially in highly mobile VANETs.

Fisheye State Routing (FSR) [Iwata et al., 1999] is an efficient link state routing that maintains a topology map at each node and propagates link state updates with only immediate neighbors instead of the entire network. Furthermore, the link state information is broadcast in different frequencies for different entries depending on their hop distance to the current node. Entries that are further away are broadcast with lower frequency than ones that are closer. The reduction in broadcast overhead is traded for the imprecision in routing. However, that imprecision gets corrected as packets approach progressively closer to the destination.

Destination Sequenced Distance Vector (DSDV) [Perkins and Bhagwat, 1994] is a table-driven routing scheme for ad-hoc mobile networks based on the Bellman-Ford algorithm. Each entry in the routing table has a sequence number, if a link is present then the sequence numbers are even otherwise an odd number is used. The sequence number is generated by the destination and the emitter must send out the next update with this number. Routing information is distributed between nodes through sending full dumps infrequently and smaller incremental updates more frequently. For the route selection, when a node receives a new information from other neighboring member then it uses the latest sequence number. If the sequence number is the same as the one already in the table then the route with better metric is used. The advantages of DSDV are that the availability of paths towards all the destination in are always shows that for these path set up a less delay is required. Also, DSDV provide the method of incremental update with sequence number labels. On the other hand DSDV have some disadvantages as well such as, it requires a regular update of its routing tables with its toplology changes which uses up battery power and a small amount of bandwidth even when the network is idle.

3.1.1.3 Hybrid Routing

Hybrid routing protocols are the combination of both reactive and proactive routing schemes. This means that hybrid routing protocols utilize features from both schemes. For example, Zone Routing Protocol (ZRP) [Haas and

Pearlman, 2001] is such a hybrid protocol and it the network can be divided into several overlapping zones based on many factors such as transmission power, signal strength, speed etc. The zone is defined as the collection of nodes which are in a zone radius. The size of zone is determined by a radius of length α, where α is the number of hops to the perimeter of the zone. ZRP makes use of proactive routing protocols in intra-zone communication and an inner-zone reactive routing protocols used in intra-zone communication. Search throughout the global network can be performed efficiently by reactively querying selected nodes in the network as opposed to querying all the network nodes.

3.1.2   Geographic Based Routing Protocols

Geographic based routing protocols rely on the geographical information in the routing process. In these protocols, the source node sends packets to the destination using its position rather than using its network address [Altayeb and Mahgoub, 2013]. These protocols require each node to be able to retrieve its location and the location of its neighbors through a location service such as the Geographic Position System (GPS) [Flury and Wattenhofer, 2006] [jinyang Li et al., 2000]. When the source node needs to send a packet, it usually stores the position of the destination in the packet header which will help in forwarding the packet to the destination without an explicit route discovery and route maintenance process. Therefore, geographic based routing protocols are considered to be more stable and suitable for large scale networks such as VANETs, compared to topology-based routing protocols. Their primary problem in highly mobile scenarios, however, is possible invalidation of positional information.

Alleviating that problem, Vehicle Assisted Data Delivery (VADD) protocol [Zhao and Cao, 2008] belongs to the Delay Tolerant Network (DTN) routing strategies aiming at improving routing in disconnected vehicular networks by the idea of carry-and-forward based on the use of predictable vehicle mobility. A vehicle makes a decision at a junction and selects the next forwarding path with the smallest packet delivery delay. A path is simply a branched road from an intersection. The expected packet delivery delay of a path can be modeled and expressed by parameters such as road density, average vehicle velocity, and the road distance. Under moderate assumptions, the minimum delay can be solved by a set of linear system equations.

Geographical Opportunistic Routing (GeOpps) [Leontiadis and Mascolo, 2007] is another example of a delay tolerant geographic routing protocol,

which takes advantage of the suggested routes of vehicles' navigation system to select vehicles that are likely to move closer to the final destination of a packet. It calculates the shortest distance from the packet destination to the Nearest Point (NP) of a vehicle's path and estimates the corresponding arrival time of the packet to its destination. The minimum delay used by VADD is indirectly obtained by selecting the next forwarding node whose path's nearest point is closest to the destination. GeOpps requires navigation information to be exposed to the network, thus privacy such as vehicle's whereabouts might be an issue.

Geographic Delay Tolerant Networks + Navigator (GeoDTN+Nav) [Cheng et al., 2010] is a hybrid routing protocol which uses both features of DTN and Non-DTN routing. GeoDTN includes the greedy mode, the perimeter mode and the DTN mode together. It switches from non-DTN mode to DTN mode by estimating the connectivity of the network based on the number of hops a packet has traveled so far, neighbor's delivery quality, and neighbor's direction with respect to the destination. The delivery quality of neighbors is obtained through a Virtual Navigation Interface (VNI), which abstract information from navigation system.

Contention Based Forwarding (CBF) [Holger et al., 2004] is a non-beacon non-DTN geographic first contention based routing protocol that does not require proactive transmission of beacon messages i.e. HELLO messages. Contrary to the traditional protocol where the forwarder actively decides its next hop but in CBF the next hop is selected through a distributed contention process by all neighbors receiving the packet: the possible forwarder waits for the time which is reciprocal to its geographic progress to the destination. Data packets are broadcast to all direct neighbors and the neighbors decide whether they should forward the packet. The actual forwarder is selected by a distributed timer-based contention process based on the actual positions of all current neighbors which allows the most suitable node to forward the packet. For the contention process, CBF makes use of biased timers. To avoid packet duplication, the first node that is selected suppresses the selection of further nodes. The receivers of the broadcast data would compare their distance from the last hop to the destination. The bigger the difference, the larger is the progress and the shorter is the expected times.

TOpology-assist Geo-Opportunistic Routing in Urban Vehicular Grids (TO-GO) [Lee et al., 2009] is another routing protocol developed for urban scenarios. TO-GO is a geo-opportunistic routing protocol that requires previous knowledge of the VANET topology in order to select the next

forwarder node. For this purpose, each node in TO-GO must construct a 2-hop neighbors table by means of periodic beacon messages. In addition to the next forwarder node, the transmitter node selects a set of backup nodes by means of a complex procedure involving the use of Bloom filters [Deke et al., 2010]. The chosen forwarder node and the set of backup nodes form a forwarder set that uses a distance-based timer to determine which node will retransmit the packet first. In order to avoid the broadcast storm problem, every node in the forwarder set must be able to hear each other. However, it is important to take into account that the Bloom filter can give false positives in dynamic data sets [Deke et al., 2010], thus possibly causing unwanted transmissions. Although [Lee et al., 2009] reports good performance metrics for TO-GO when considering a non-ideal path loss model, the implemented channel was not explicitly developed for V2V scenarios. Finally, it is worth mentioning that TO-GO does not implement a location discovery service.

The Greedy Perimeter Stateless Routing (GPSR) [Karp and Kung, 2000] algorithm belongs to the category of position based routing, where an intermediate node forwards a packet to an immediate neighbor which is geographically close to the destination. This approach is called greedy forwarding. For this purpose, each node needs to be aware of its own position, the position of its neighbors and as well as the position of the destination node. It is assumed that each node is able to obtain its own position using GPS devices, exchange it with neighboring nodes by beacon messages, and obtain the position of the destination node by a separate location service. However, the recovery strategy of GPSR is inefficient and time consuming especially in highly dynamic VANET environments. In addition, GPSR is best suited to open environments with even distribution of nodes but greedy forwarding is often restricted to a city scenario, because the direct communication typically does not exist under the presence of obstacles.

Greedy perimeter coordinator routing (GPCR) [Lochert et al., 2005] is both a position-based routing protocol using standard greedy forwarding and a repair strategy that does not require a graph planarization algorithm. A graph is said to be planar if it can be drawn on the plane in such a way that no two of its edges cross. For example, a graph G=(V,E) with vertex set V and edge set E, the objective of graph planarization is to find a minimum cardinality subset of edges F⊆E such that the graph G'=(V,E / F), resulting from the removal of the edges in F from G, is planar [Resende and Ribeiro, 2008].

GPCR was proposed to improve the reliability of GPSR [Karp and Kung, 2000] in VANET. The main idea of GPCR is to take advantage of the fact that streets and junctions form a natural planar graph, without using any global or external information such as a static street map. GPCR consists of two parts: a restricted greedy forwarding procedure and a repair strategy and junctions. Therefore it does not need a graph planarization algorithm. In the restricted greedy forwarding of GPCR, junctions are the only places where actual routing decisions are made. Therefore, packets should always be forwarded to a node on a junction rather than being forwarded across a junction. A coordinator broadcasts its role along with its position information. If the forwarding node is located on a street and not on a junction the packet is forwarded along the street towards the next junction. Once a packet reaches a coordinator a decision has to be made about the street that the packet should follow. This is done in a greedy fashion: the neighboring node with the largest progress towards the destination is chosen. As a consequence, the repair strategy of GPCR consists of two parts: (1) on each junction it has to be decided which street the packet should follow next, and (2) in between junctions a special form of greedy forwarding is used to forward the packet towards the next junction. Given that no external map is available, the key challenges are to identify nodes that are on a junction and to avoid missing junctions while greedy forwarding is used [Lochert et al., 2005]. Therefore, the basic behavior of GPCR is similar to GPSR, but it selects a relay node after considering information about the road structure. GPCR makes routing decisions on the basis of streets and junctions instead of individual nodes and their connectivity. However, GPCR forwards data packets based on the node density of adjacent roads and the connectivity to the destination. Thus, if the density of nodes is low or there is no connectivity to the destination, then the delay time increases and the local maximum problem goes unresolved [Chao and Ryu, 2012].

Connectivity-Aware Routing (CAR) [Numov and Gross, 2007] is a suggestion following up on the work on Preferred Group Broadcast (PGB) to minimize broadcast from AODV route discovery and Advanced Greedy Forwarding (AGF) to account for node mobility in VANETs. CAR uses AODV-based path discovery to find routes with limited broadcast range from PGB. However, nodes that form the route record neither their previous node from backward learning nor their previous node that forwards the path reply packet from the destination. Rather, anchor points, which are nodes near a crossing or road curve, are recorded in the path discovery packet. A node determines itself as an anchor point if its velocity vector is not

approximately parallel to the velocity vector of the previous node in the packet. The destination might receive multiple path discovery packets if it chooses the path that provides better connectivity and lower delays.

AGF is then used to forward the route reply back to the source via the recorded anchor points. When the source receives the route reply, it records the path to the destination and starts transmitting. Data packets are forwarded in a greedy manner toward the destination through the set of anchor points using AGF. In addition to handle mobility by AGF, CAR introduces 'guards' to help tack the current position of a destination. A guarding node can filter or redirect packets or add information to a packet that will eventually deliver this information to the packet's destination.

Geographic Source Routing (GSR) [Liu et al., 2008] relies on the availability of a map and computes via a Dijkstra algorithm a shortest path on the overlaid graph where the vertices are junction nodes and the edges are streets that connect those vertices. The sequence of junctions establishes the route to the destination. Packets are then forwarded greedily between junctions. GSR does not consider the connectivity between two junctions; therefore, the route might not be connected through junctions. Recovery when such a case happens is greedy forwarding. The major difference between GSR and CAR is that CAR does not use a map and it uses proactive discovery of anchor points that indicate a turn at a junction.

Greedy Perimeter Stateless Routing Junction+ (GpsrJ+) [Lee et al., 2007a] is proposed to further improve the packet delivery ratio based on minimal modification of GPCR. GpsrJ+ utilizes two-hop beaconing to predict the next road segment in which the packet should be forwarded toward a destination. If the current forwarding node has the same direction as a coordinator node, the prediction mechanism bypasses the intersection and forwards the packet to the node ahead of the junction node. However, if the coordinator node has a different direction from the current forwarding node, it selects the coordinator node as a next relay hop. In comparison with GPCR and GPSR, GpsrJ+ increases packet delivery ratio and reduces the number of hops in the perimeter mode of packet forwarding.

Anchor-based street and traffic Aware Routing (A-STAR) [Boon-Chong et al., 2004] is an operable routing protocol in city environments. It removes one of the drawbacks of GSR by taking into account the vehicular traffic on the street. A-STAR makes use of vehicular traffic on the street and then assigns weight to each street according to the number of bus lines that the road possesses. The more bus lines a road owns, the less weight

it is assigned and vice-versa. A digital map facilitates the computation of anchors or junctions by using Dijkstra shortest path algorithm. Packet relaying from source to destination is based on greedy forwarding algorithm. When packets get stuck in a local maximum, a new recovery strategy is introduced. The road segment where the local maximum problem occurs is marked as "out of service" for a short duration and this information is propagated throughout the network so that other data packets can avoid this "out of service" street. The A-STAR routing protocol is traffic aware by considering the number of bus lines but it does not take into account vehicular traffic density. Otherwise, most of the network traffic is shifted towards major streets owning many bus lines (and therefore may induce bandwidth congestion) rather than secondary streets, even if these streets provide better connectivity and may supply the actually best path.

Greedy Traffic Aware Routing (GyTAR) [Jerbi et al., 2006] is an intersection-based geographical routing capable of finding robust routes within city environments. GyTAR requires the existence of an accurate traffic information system to select routing paths. It takes into account the position of the junctions to decide the next hop for each packet. When a local optimum is discovered, the packet is carried by the vehicle until a junction is reached.

Street Topology Based Routing (STBR) [Forderer, 2005] went further than A-STAR by computing the road connectivity at junction nodes. One of the nodes at a junction is selected as a master which is responsible for checking if links to the next junctions are up or down. Within the broadcast from every master, there is also link information to all neighboring links. This is because every master will receive every other master's link information. Thus, every master contains a two-level junction neighbor table. The first level is through neighboring links to its direct junction nodes. The second level is its direct junction nodes through their neighboring links to their own junction nodes. In STBR, packets are routed based on their geographic distance to the street where the destination is located. This is different from GSR or A-STAR where routes are computed through Dijkstra shortest path.

Landmark Overlays for Urban Vehicular Routing Environments (LOUVRE) [Lee et al., 2008] has summarized geographic greedy overlay routing into two camps. The first camp is geo-reactive overlay routing where the next overlaid node is determined based on their neighboring nodes' distance to the destination (STBR) or a combination of it and traffic density (GyTAR). The second camp is geo-proactive overlay routing where the sequence of overlaid nodes is determined a priori (GSR and A-STAR). LOUVRE

belongs to the second camp. It takes note of the fact that above a given vehicular density threshold, an overlay link remains connected regardless of the vehicular spatio-temporal distribution on the link. Thus, by only considering overlay links based on such density threshold when establishing overlay routes, most routes would partially use the same overlay links. With these considerations, geo-proactive overlay routing becomes attractive as it guarantees global route optimality and reduces the delay for establishing overlay routes. The drawback of this approach is obviously its scalability.

MUltihop Routing protocol for Urban VANETs (MURU) [Mo et al., 2006] is related to the TASR [Khan and Fränzle, 2015] protocol suggested in this thesis. The authors introducing MURU tried to balance hop minimization with its ability to provide a robust route connection. In doing so, a new metric called the Expected Disconnection Degree (EDD), is introduced to estimate the quality of a route based on factors such as vehicle position, speed and trajectory. MURU requires each vehicle to know its own position and to have an external static street map available. The presence of an efficient location service is also assumed. By broadcasting the route request message, the path with the smallest EDD is selected as the route. MURU provides routes minimizing the hop count. MURU is loop-free and as MURU always chooses a path from source to destination with the smallest EDD, it aims to provide a quality route that delivers a high percentage of packets while controlling overhead and delay. MURU achieves a reasonable packet delivery ratio, but the selected end-to-end path may some times be invalid as mobility of vehicles can induce network partitioning. Furthermore, it requires the network to be generally fully connected and can tolerate only a few seconds of network disconnection.

The Vehicle Density and Load-Aware (VDLA) routing protocol [Zhao et al., 2012] [Li et al., 2014] is based on sequential intersection selection to construct a route. The protocol determines the real-time traffic load and density with destination distance and collects all the information through a centralized mechanism, which obviously provides a bottleneck. The protocol computes these routing metrics (real-time traffic load and density with destination distance), and the packets avoid the disconnected roads with load balancing in order to mitigate network congestion. To realize the mechanism, each node adds the length of its buffer queue to the HELLO packets which are broadcasted periodically, and this information stored int eh neighbor table, The collection is started by the nodes located at junctions. For a certain road segment, when when the collected information is transmitted from one end to the other end, the vehicle density and the

traffic load are achieved [Zhao et al., 2012]. The protocol has the ability to reduce unnecessary hops by selecting the intermediate junctions before a packet reaches a junction. For routing, VDLA prefers roads that are well-connected with lower traffic loads. However, the protocol adds the Network Information Collection Packet (NICP) which includes a number of nodes and the total length of the buffer queue and total neighbors and transmits it from one end to the other. The underlying process of the VDLA protocol is a step where vehicle A activates the NICP and the farthest neighbor node B adds the information and the updated packet is forwarded to node C. Node C repeats the same method until the packet reaches the designated destination. The protocol suffers from network overhead due to the addition of the NICP and the exchange of the complete road information in the hello messages.

Junction-Based Routing (JBR) [Tsiachris et al., 2012] is another geographic junction-based routing protocol utilizing selective greedy forwarding to a node that is located at a junction closer to the destination. By combining the function of GPS and geographic data systems, JBR allows noes to learn more accurately about their location such as road segments (streets) and junctions. Nodes are divided into two classes: coordinators located at junctions and simple nodes placed in the middle of a road segment, i.e. the road between junctions. If there is a coordinator available, it will be prioritized. The closest one to the destination is selected as the next hop instead of a random selection. The key novelty of JBR is the minimum angle method as in the recovery mode, junction nodes also maintain the highest relay priority. The basic practice will be connecting each of the nodes in this transmission range including the one that enters the recovery mode and all other to the destination node and take the node with the smallest connection angle to the destination as the next relay node.

3.1.3 Cluster Based Routing Protocols

Cluster Based Routing (CBR) [Luo et al., 2010b] is a protocol where the geographical area is divided into a finite set of logical grid elements and each of them will have an exclusive ID. Only if there is some vehicle in the grid element will a vehicle be elected as Cluster Head (CH) for the area covered by the grid element, and data packets be routed by the cluster head across some grid one by one. When the source node wants to send a message to the destination node, it does not discover the route and save route table but send the data packet to the optimal neighbor cluster header directly according to the geographic information (including itself, neighbor cluster header's and the destination's geographic information). Then the

neighbor cluster header which received the data packet will forward the packet according to this policy until it arrives at the destination node. The optimal neighbor CH selection process that selects neighbor CH having minimum angle between when compared with other neighbor CH. The data packets forwarding is done after the CH has been elected and has forwarded the data packet. The greatest advantage of CBR protocol is that it reduces the overhead and packet delivery delay when transporting a data packet to the destination node. It increases the packet delivery ratio and saves the memory space of caching the routing table.

Cluster-based Directional Routing Protocol (CBDRP) [Song et al., 2010] was designed especially for highway scenarios in which the Cluster Head (CH) selects one more CH based on moving direction of vehicle. A node in a cluster broadcasts an 'apply packets' containing location of cluster it own state vector information (location, direction, velocity etc.) which is received by each node in cluster including the CH. The current CH replies with another 'apply packet' which contain details such as location of the cluster along with its location and velocity of another node which is in the center of the cluster and not a CH. If the node does not receive the 'apply packet' will become CH. CBDRP gives high link stability and high packet delivery ration.

The Affinity Based Clustering Routing (ABCR) [Bhaumik et al., 2012] protocol comprises of three different phases. In this routing protocol the geographical location is divided into clusters, based on type of infrastructure & traffic and also on the possible travel speed of the vehicles The protocol's functionality can be summarized as follows: at first, Cluster Head (CH) selection mechanism has been executed by affinity propagation i.e. cluster members are guaranteed to be in the transmission range of the cluster head due to the cluster geometry. In the next step cluster member selection and cluster formation procedure has been presented i.e. the cluster head maintains information about all the cluster members. In the third step communication procedure has been executed through inter cluster and intra-cluster communication. Therefore, cluster members do not take part in intra-cluster communication, which is the sole responsibility of the cluster head.

3.1.4   Geocast Based Routing Protocols

In this type of routing protocol, a specific geographical region is defined so that forwarding of packets from source to destination is achieved by flooding or geocasting.

Inter-Vehicular Geocast (IVG) [Bachir and Benslimane, 2003] was proposed to inform all vehicles located in a risk area, then called a multicast group, about any danger on the highway such as when a vehicles collision occurs. To achieve this goal, the risk area is determined by considering the precise obstacle location on the road and the driving directions that can be affected. The damaged vehicle broadcasts an alert message to its vicinity, thereby identifying the risk area or, equivalently, description of the multicast group determined by the above considerations. The neighbors receiving the message test its relevance according to their location by relating it to the affected risk area. All neighbors belonging to the risk area calculate a different time backoff that prioritizes the furthest away node in order to be a relay in rebroadcasting the message. Obviously, more distant is more favorable for fast spread of the broadcast. This relay selection technique makes use of periodic beacons unnecessary.

The Distributed Robust Geocast (DRG) [Joshi, 2006] is a protocol, where all nodes participate that satisfy a set of geographical criteria for which the geocast message is still pertinent. The Zone Of Forwarding (ZOF) is the set of nodes eligible to forward the Geocast message. The authors proposed a forwarding algorithm based on more relays selection instead of single relay for the data packet forwarding. In this sense the relay node is intermediate node towards the destination. DRG takes place in the manner that each vehicle when receiving a geocast message tests its relevance according to its location. If the vehicle belongs to the Zone Of Relevance (ZOR) then it reads the message. Otherwise, if the vehicle is in the ZOF then it forwards the message, else the message is dropped. It should be noticed that DRG also does not need to exchange periodic beacons.

Reliable Geographical Multicast Routing in Vehicular Ad-hoc Networks (ROVER) [Kihl et al., 2007] presents a technique similar to AODV which consists in broadcasting only control packets, while data packets are unicasted and a periodic beaconing system is utilized. ROVER's underlying assumptions consist of the following:

1. Each vehicle is identified by an identification number;

2. Each vehicle is equipped with a GPS receiver;

3. Vehicles have access to a digital map;

4. ZOR is a rectangular area;

5. ZOF includes the sender and the ZOR.

The goal of ROVER is to deliver an application-generated message to all vehicles located into the specified ZOR. ROVER defines a message as a triplet containing application, message and ZOR. A vehicle considers a message if it belongs to the message's ZOR.

3.1.5   Broadcast Based Routing Protocols

This class of routing protocols uses simple flooding over the network in order to reach all vehicles. Different relay selection techniques are used to reduce the message overhead.

Broadcast Communication (BROADCOMM) [Durresi et al., 2005] is based on a hierarchical structure for highway networks. In BROADCOMM, the highway is divided into virtual cells which move like vehicles. The nodes in the highway are organized into a two-level hierarchy: the first Level includes all the nodes in a cell and the second level is represented by cell reflectors, which are a few nodes located closest to the geographical center of cell. Cell reflectors behave for a certain interval of time as cluster head and handles the emergency messages coming from members of the same cell or nearby neighbors.

The Selective Reliable Broadcast (SRB) [Vegni et al., 2012] protocol is a reliable cluster-based routing protocol that is expected to minimize the number of rebroadcast messages. SRB considers the cluster selection process and the cluster-head election by exploiting the inter-vehicle distance and the time delay. Via simulation results, the proposed technique results in an efficient method to detect clusters and alleviate the broadcast storm problem.

The Urban Multihop Broadcast (UMB) [Korkmaz et al., 2004] protocol is designed to overcome interference, packet collision and hidden-node problems during message distribution in multihop broadcast. In UMB the sender node tries to select the farthest node in the broadcast direction for forwarding and acknowledging the packet without any prior topology information. The UMB protocol performs well at higher packet loads and vehicle traffic densities.

Broadcast routing is mainly used for safety applications such as for sharing weather report, traffic information, road condition among vehicles and delivering different vehicular advertizements and announcements. Broadcasting is to be used when message is to be sent to the designated destination vehicle beyond the transmission range i.e. multihops. During the broadcasting same message is send to all the members within the network, typically

using flooding. For the small number of participants in VANET networks, broadcast routing outperforms which ensures the delivery of the data packet. In contrast, for the larger density of participants, this causes exponential increase in bandwidth. The above presented broadcast routing protocols did not showed the satisfaction that can control the message overhead.

The following Figure 3.2 shows the complete evaluation of the well known selected routing protocols evaluation.

Routing Protocols	Forwarding Strategies					Recovery Strategies			Scenario		Digital Map		QoS Parameters								
													CPO		Scalability		Delay		Delivery		PDR
	Greedy	Trajectory	Opportunistic	Hybrid	Multihop	Flooding	Store & Forward	Node Awareness	Highway	City	Yes	No	High	Low	Good	Poor	More	Less	Guaranteed	Best Effort	Upto 80%
AODV					✓	✓											✓			✓	✓
PGB	✓					✓				✓	✓		✓		✓		✓			✓	✓
JBR	✓					✓				✓	✓			✓	✓			✓		✓	✓
FSR		✓				✓						✓			✓			✓	✓		
DSDV		✓				✓						✓			✓		✓			✓	✓
ZRP				✓		✓						✓	✓				✓			✓	✓
GyTAR	✓						✓			✓	✓			✓	✓			✓	✓		✓
VADD			✓						✓		✓							✓	✓		✓
GeOpps			✓						✓		✓						✓		✓		✓
CBF	✓								✓		✓		✓		✓		✓			✓	✓
TO-GO	✓								✓								✓		✓		✓
GPSR					✓				✓		✓						✓			✓	✓
GPCR					✓	✓			✓	✓		✓		✓	✓			✓		✓	✓
CAR		✓						✓	✓	✓	✓			✓	✓			✓		✓	✓
AGF	✓					✓														✓	✓
GpsrJ+	✓						✓			✓		✓		✓	✓			✓	✓		✓
A-STAR	✓									✓	✓				✓		✓		✓		✓
STBR		✓				✓				✓		✓		✓			✓			✓	✓
LOUVRE	✓									✓	✓						✓			✓	✓
MURU		✓				✓				✓	✓				✓			✓	✓		✓
CBDRP					✓	✓			✓		✓		✓		✓		✓		✓		✓
ABCR																					✓
IVG	✓					✓			✓				✓		✓		✓			✓	✓
DRG	✓					✓							✓		✓		✓			✓	✓
ROVER	✓					✓			✓				✓			✓	✓			✓	✓
BROADCOMM					✓				✓			✓		✓			✓			✓	✓
UMB					✓	✓				✓	✓			✓	✓			✓		✓	

Figure 3.2: Comparison of well known selected routing protocols.
CPO-Control Packet Overhead, PDR-Packet Delivery Ratio, QoS-Quality of Service.

3.2 Selected Packet Forwarding Algorithms in VANETs

The dynamic nature of vehicular communication due to high speed of vehicles and mobility results in degraded performance of traditional routing

protocols. Because of these unique features, robust VANET routing protocols need an appropriate data forwarding mechanism, which is a crucial issue in their design. Currently, there are different forwarding strategies available in the literature. Some of them are discussed in this section.

In order to cope with the problems of scalability and reliability during the data packet forwarding, most of the VANETs routing protocols utilize geographical forwarding for data packets transmission. In the literature of geographical forwarding [Yong et al., 2007] [Karp and Kung, 2000] [Lochert et al., 2003] [Luo et al., 2010a], each node in these cited forwarding algorithms next hop selection is selected in such a way as to minimize the forwarding progress (e.g. these neighbor are mostly on the transmission range and closest to the destination). This process continues until the data packet reaches the appropriate destination node. Obviously, to successfully choose next hops, it is vital for each node to maintain an accurate neighbor list. Otherwise, the best next hop could be missed or even worse, a node which is already out of the transmission range is chosen as the next hop.

To solve this problem, Greedy perimeter stateless routing with an Advance Greedy Forwarding (Greedy+AGF) mechanism was proposed [Numov and Gross, 2007].

In the Greedy+AGF algorithm both the source and destination nodes inform each other about their velocity vectors. Additionally, the packet processing and packet transmission times are added to their data packet header file. When a node is willing to transmit the data packet to the designated node, it investigate in the neighbor table for the list of intermediate node and their state of vector information if these are still reachable to the designated node. If the destination node entry is still in the neighbor table but the node is, based on position prediction, considered likely to travel out of its communication range during the data packet relaying process, then the next hop is chosen that is closest to the predicted position. If the destination node is not found in the neighboring table, the forwarding node consults the packet traveling time and estimates whether it may potentially reach the position of the destination node within one hop transmission. Furthermore, if the designated node is found to be reachable, then the data packet is directly forwarded to the destination. Otherwise, it will transmit the data packet to the next closest hop and then the process repeats.

However, the above two geographic forwarding algorithms sometimes make data packets fall into local maxima (where the node fails in determine the next-hop neighbor to continue forwarding the packet towards the destina-

tion) and then initiate a repair strategy, which does not perform well in city scenarios because their layout are based on a distributed algorithm. The authors in [Lochert et al., 2005] proposed an algorithm which just makes use of a restricted greedy forwarding algorithm to overcome the trapping by local maxima. In this algorithm, data packets should be forwarded to a node on an intersection in a greedy manner rather than to a node which is furthest from the current forwarding node but within its communication range. In addition, a few link-aware routing schemes also have been reported in [Souryal and Moayeri, 2005] [Lee et al., 2005], but the link duration between vehicles in the vicinity is very short due to high mobility. In [Leontiadis and Mascolo, 2007], the author proposed an algorithm which utilizes trajectory based geographic method to choose the next hop. In this method, according to the suggested routes and to their own destination, neighboring nodes firstly calculate the nearest point that they will pass through to the data packet's destination, and they then make use of a function expression which is based on the information of the nearest point and digital map, in order to estimate the minimum time that this data packet requires to reach its destination. Finally, the neighboring node that can deliver this data packet to its destination with the shortest time becomes the next hop. However, these geographic forwarding algorithms require proactive HELLO message broadcasts, which consume enormous resources and occupy significant bandwidth in VANET environments. So the performance of VANET routing protocols is affected, especially in peek working hours in urban scenarios.

So as to eliminate the effects of HELLO message broadcast, distributed next-hop selection algorithms were proposed in ad-hoc and sensor networks [Holger et al., 2003] [Egoh and De, 2006b] [Mohit et al., 2006] which are built on a receiver-based concept. In these relay selection approaches, the sender broadcasts a control packet informing its neighbors about a pending data packet transmission and then each neighboring node utilizes certain criteria to determine if it can be selected as a next hop candidate. If so, it calculates a waiting time, which is used to allow the better candidate to answer first. If a neighbor does not hear a better candidate before its waiting time expires, it informs the sender that it is the best next hop. The current implementations of these approaches use only one criterion to compute the waiting time (namely the distance between potential next hops and the destination), which works well under the unit disk assumption [Huson and Sen, 1995] (for example, the wireless channel is ideal and the transmission range is a circle of a fixed radius). However, many studies [Gang et al.,

2004] [Jerry and Ramesh, 2003] have proven that real wireless radios do not follow the unit disk assumption especially in VANET scenarios, where there are a lot of buildings and other obstacles to impact radio propagation. Therefore, selecting the neighbor that optimizes the forwarding progress alone does not guarantee optimal selection of the next hop. In order to solve the above challenges, some multi-criterial approaches to receiver-based next hop selection [Nzouonta et al., 2009] [Egoh and De, 2006a] have been suggested. However, these methods do not consider real wireless channel models, neighboring interferences and signal propagation models.

3.3   Chapter Summary

In this chapter, the most relevant VANET routing protocols, which are topology based, geographic based, cluster based, geocast based and broadcast based are introduced. Several data forwarding algorithms for next hop selection were investigated. Based on this literature, there are still many challenges in the field of VANET communications and this thesis will focus on network and MAC layers in the following chapters.

Part II
Robust Communication Protocols for Network Layer and MAC Layer

4. TASR:Traffic Aware Segment-based Routing Protocol for VANETs in City Scenarios

4.1 Introduction

Vehicular Ad-hoc Networks (VANETs) utilize the IEEE 802.11p protocol to provide for a variety of safety-critical services like traffic alerts or dynamic route planning [Dashtinezhad et al., 2004] [Zhou et al., 2005] [Nandan et al., 2005] [Riva et al., 2007] [Balasubramanian et al., 2008]. Such services require timely delivery which relies on bandwidth and latency. Services like traffic alerts and route planning can be exploited for applications such as detecting slow or broken down vehicles, providing wrong-way driving warnings, overtaking warnings and lane change assistance. The majority of such safety-critical applications must not exceed a latency of 100 ms

[Toor et al., 2008]. While applications that are not safety-critical are well described and standardized like long range communication (in particular cellular networks associated with smart phones [Hartenstein and Laberteaux, 2008b]), VANET specifications are less advanced and mature. Message transmission in VANETs is triggered either periodically or event-driven. Periodic messages provide preventive safety and awareness by informing drivers of primary details about other cars and the environment. They further allow to derive secondary parameters like optimal acceleration for riding the green wave (e.g. green light optimized speed advisory, GLOSA). On the other hand, event-driven messages are sent when necessary such as warning of suddenly braking vehicle in a critical situation. VANETs exploit Inter-Vehicle Communication (IVC) protocols to become part of Cooperative-Intelligent Transportation Systems (C-ITSs) environment.

The goal of such environments is to increase safety while at the same time reducing traffic and in turn fuel consumption, travel time, traffic jams [Zhao and Cao, 2008] [Sommer et al., 2011] [Chen et al., 2015]. The success of VANETs relies also on the efficiency of message routing between the mobile nodes[1]. The ad-hoc communication between two cars often relies on multiple hops that are located between these two cars. Two challenges that specifically VANETs face are i) a highly dynamically changing structure and ii) obstacles frequently blocking communication [Boban et al., 2011].

Challenges, that for instance Airborne Ad-hoc Networks (AANETs) do not suffer from to the same extent. Blocked Lines-of-Sight (LoS) in city areas are the rule rather than the exception [AAN, 2016]. Although VANETs have dynamically changing topologies, these topologies are nevertheless geometrically more constrained than in AANETs, as road vehicles have to follow the given road geometry [Berradj and Mammeri, 2015]. The presented protocols for VANETs can, however, also be exploited for AANETs. This chapter focuses on safety applications. Event-driven emergency messages have to be efficiently disseminated within a specific geographical region [Tseng et al., 2002]. The IVC dissemination protocols are the key to providing robust connectivity. The protocol presented in this chapter, Traffic Aware Segment-based Routing (TASR), is one such protocol. Challenges to robustness are i) highly dynamically changing topologies, ii) data intensive services taking bandwidth and requiring wide dissemination, and iii) spatial and temporal precision in localization.

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[1]For convenience, vehicle, car and node are treated equivalently.

One common approach for data dissemination is data flooding. Data packets are thereby disseminated into a wide area with low delay. Still, if data flooding is not properly controlled, a 'broadcast storm' may occur [Tian et al., 2016]. Additionally, established routes break frequently due to node mobility and LOS obstructions. One approach overcoming the shortcomings of the naïve data flooding approach is Dedicated Short-Range Communication (DSRC), which is one of the foundations for the TASR protocol suggested in this chapter. Wireless Access in Vehicular Environment (WAVE) is the core part of DSRC. It concludes a suite of IEEE P1609.x standards focused on the MAC and network layers. WAVE is fairly complex and built over the IEEE 802.11 standards by amending many tweaks to provide for fast and reliable exchange of safety messages. The density of vehicles equipped with DSRC is low, the IEEE 802.11p standard does not establish a Basic Service Set (BSS) (authentication and association procedures are not required), and the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism of IEEE 802.11p lacks an acknowledgment process. These properties speed up the connection process at the cost of unreliable broadcasting connectivity. A recent trend in relevant routing protocols is to exploit geographical information for selecting paths based on estimating road traffic conditions in situ. The cost is commonly a high communication overhead for gathering also non-local traffic information. The estimated traffic density is an important measure for real time applications in vehicular networks especially in urban environments. Traffic density-based routing protocols determine traffic density by attaining density feedback from the network and forward the data packets through low and high density routes.

This chapter introduces the TASR protocol [Khan and Fränzle, 2015] [Khan et al., 2018], a locally informed multihop routing protocol for VANETs especially designed to cope with the challenges of urban environments. TASR is a fully distributed protocol that does not require any roadside infrastructure. The major routing decisions are based on the segment information which helps to select an appropriate Next-to-Next (N2N) segment.

Its mechanism is designed to improve the success probability of routing protocols by dynamically estimating the multihop forwarding capabilities of road segments and the network connectivity among them. To measure the robustness and connectivity of segments, a novel metric called Estimated Connectivity Degree (ECD) is presented. The ECD correlates with the connection probability, estimating the connectivity of nodes on the segments. Thus it can be employed to assess the connection quality of each candidate path between source and destination. After the N2N segment selection

using ECD metric, the packet forwarding phase start where the next hop is selected based on maximizing the forwarding progress, that is, by always selecting the node closest to the destination node.

This greedy process continues until the packet reaches the destination. It is vital for each en-route node to keep a precise neighbor list to select the optimal candidate. The peril here lies in a possible huge overhead as mentioned above. TASR provides a solution to control the transmission overhead in each relaying node to eliminate broadcasting in the whole transmission region. At the same time, TASR provides for a robust communication meaning i) maximal connectivity probability, ii) minimal network delay, iii) optimal bandwidth exploitation and iv) low error rate.

The remainder of this chapter is organized as follows: Section 4.2 motivates the development of the TASR protocol. Related work employing different routing techniques from the selected literature is presented in Sect. 4.3 and Section 4.4 then presents the system model for the proposed routing protocol. Section 4.4 presents the system model and Section 4.6 describes our proposed routing protocol named Traffic Aware Segment-based Routing (TASR) along with its data-packet forwarding technique. Detailed evaluation results are shown in Section 4.9 and the chapter concludes with a discussion in Section 4.10.

4.2   Motivation

The application of Vehicular Ad-hoc Networks (VANETs) is promising safer roads and smooth driving by implementing a large spectrum of safety applications ranging from traffic alert dissemination and dynamic route planning to context-aware advertisement and file sharing [Dashtinezhad et al., 2004] [Zhou et al., 2005] [Car,] as discussed in the previous chapter Section 2.1. These latter applications require that their alert information is propagated to the concerned vehicles such as those located in the hazardous zone, with a minimum delay and a high reliability. For these reasons, this category of applications are considered as being of delay-sensitive and broadcast-oriented nature. Furthermore, the network traffic overhead from periodic 'Hello' messages negatively impacts the end-to-end data transfer. Considering the large number of nodes participating in urban networks and their high mobility, debates still prevail about the feasibility of applications using end-to-end multihop vehicular communication. To this end, this chapter proposes a solution to this problem such as a modified geographic greedy forwarding algorithm, which increases significantly the average data

delivery ratio by reducing the overhead associated with the selection of the next hop node in congested networks.

The major apprehensive is whether the VANET routing protocols can fulfill and satisfy the basic requirements such as necessary throughput and delay since routing performance depends on the VANETs type. The VANETs type can be varied by its characteristics such as node density and average speed differ in cities, highway and suburban areas. This chapter 4 focuses on VANET routing in city based scenarios where the communication is Vehicle-to-Vehicle (V2V) only.

4.3   Related Work

This section reviews selected VANET routing protocols. They can broadly be classified into two categories: Topology and position based. Both types exploit the node location to instantaneously select the next relay node. Topology-based protocols consider each node to have information about the entire network topology before forwarding messages. In contrast, position-based routing protocols can also work with partial location information.

One early work on position-based protocols is Greedy Perimeter Stateless Routing (GPSR) [Karp and Kung, 2000], which combines greedy routing with a face routing mechanism. Face routing is a recovery strategy such as face routing is necessary to assure that a message can be delivered to the destination. It routes packets to the neighboring node that has the shortest distance to the destination node. Face routing allows to get out of local minima when greedy routing fails. It performs well in an open-space scenario with evenly distributed nodes — properties not regularly encountered in urban VANETs. In addition, with the rapid movement of vehicles, routing loops can be introduced while in the perimeter mode of GPSR .Consequently, the authors of [Tsiachris et al., 2012] reported that GPSR does not performs well in urban environments. In detail, when the current node fails to find a neighbor closer to the destination than itself (which is known as the local maximum problem), the greedy forwarding strategy is switched to a recovery mode. Packets are forwarded along the perimeter of a planar network graph with no crossing edges based on the right-hand rule. Greedy Perimeter Coordinator Routing (GPCR) [Lochert et al., 2005] enhanced GPSR by considering the characteristics of VANETs. GPCR adopted a restricted greedy forwarding to forward packets along the roads. Although GPCR cannot prevent from incurring local maxima after starting to forward in the chosen destination. As a result, it might

not always ensure reliable end-to-end transmissions. GSR (Geographic Source Routing) [Liu et al., 2008] relies on the availability of a map and computes a Dijkstra shortest path on the overlaid graph where the vertices are junction nodes and the edges are streets that connect those vertices. The sequence of junctions establishes the route to the destination. Packets are then forwarded greedily between junctions. GSR does not consider the connectivity between two junctions; therefore, the planned route might not be connected through. Recovery when such a case happens is greedy forwarding. The major difference between GSR and CAR is that, CAR does not use a map and it uses proactive discovery of anchor points that indicate a turn at a junction. GreedY Traffic Aware Routing (GyTAR) [Jerbi et al., 2006] is an intersection-based geographical protocol for finding robust routes within city environments. GyTAR requires an accurate traffic information system to select routing paths. It takes the position of the junctions into account to decide the next hop for each packet. When a local optimum is discovered, the packet is carried by the vehicle until a junction is reached. Intersection-based Geographical Routing (IGRP) [Saleet et al., 2011] provides an efficient selection of road intersections for a packet to pass through. Routing via road intersections is based on the same four premises as TASR such as maximal connectivity probability, minimal network delay, optimal bandwidth exploitation and low error rate. Contention-Based Forwarding (CBF) [Holger et al., 2004] is a geographic ad-hoc routing protocol. A sender broadcasts and the receiving neighbors will select one among them to relay the packet. The protocol is ideal for rural regions without obstacles as local maxima do not occur there. Consequently, CBF does not performs well in urban environments, where local maxima occur on different possible paths connecting source and destination. TOPOlogy-aware Contention-Based Forwarding (TOPOCBF) [Rondinone and Gozalvez, 2011] is a routing protocol for VANETS extending CBF. In this protocol, the selection of routing paths is based on a direct estimation of their multi-hop connectivity and not only on vehicular density. To cope with the challenges arising with dynamic topologies, in which the network is not always connected, another group of routing protocols is proposed in the literature [Ahmed and Kanere, 0016] [Ding et al., 2007] [LeBrun et al., 2005] [Leontiadis and Mascolo, 2007]. These routing protocols can be considered as realizing delay-tolerant protocols applicable to delay-tolerant applications and the carry-and-forward scheme is applied when partial disconnects from the network occur. They occur frequently in rural highway situations and in cities at night when too few vehicles are in the streets to

establish end-to-end routes. Even in densely-populated urban scenarios, sparse sub-networks can also be prevalent. There can be multiple relaying carriers between source and destination. Each carrier is selected due to the highest predefined direction priority. Although this approach predicts the direction of vehicle movements, it does not predict any future change in the topology. Junction-Based geographic Routing (JBR) [Tsiachris et al., 2012] is a routing protocol utilizing selective greedily forwarding to a node that is located at a junction closer to the destination. Nodes are divided into two classes: Coordinators located at junctions and simple nodes placed in the middle of road segments like vertices and edges of a graph. When available, coordinators prioritize. The closest node to the destination that is reachable is selected as the next hop. The key novelty of JBR is the minimum angle method. The intersection-based geographical routing protocol introduced in Traffic Adaptive Data dissemination (TrAD) [Tian et al., 2016] is a protocol which i) does not require infrastructure and ii) takes road and network traffic into account for both highway and urban scenarios. TrAD has double broadcast suppression techniques and is designed to adapt to an irregular road topology. The traffic density and load-aware routing (VDLA) protocol, as proposed in [Li et al., 2014], is based on sequential intersection selection to construct a route. The protocol determines the real-time traffic load and density. Information is collected via a centralized mechanism. The protocol avoids disconnected roads and exploits load balancing to mitigate network congestion. It reduces unnecessary hops by selecting intermediate junctions before a packet reaches a junction. Well-connected roads with low traffic loads are preferred. However, the protocol adds a Network Information Collection Packet (NICP) which includes i) a number of nodes, ii) the total length of the buffer queue, and iii) the total number of neighbors. The MUlti-hop Routing protocol for Urban VANETs (MURU) [Mo et al., 2006] is comparable to the proposed TASR protocol. MURU balances hop minimization with the ability to provide a robust route connection. A metric referred to as Expected Disconnection Degree (EDD) allows to estimate the quality of a route based on factors such as vehicle position, velocity and trajectory. MURU requires each vehicle to know its own location and to have a street map available. Broadcasting route requests allows to determine the path with the smallest EDD. MURU routes with a minimal number of relay hops. MURU is loop-free (i.e. acyclic) and always selects a path from source to destination with the smallest EDD. It balances the number of successfully transferred packets against overhead and delay. MURU achieves a reasonable packet delivery ratio. Nevertheless, selected paths

can become invalid as dynamic topology can induce network partitioning. Furthermore, it requires a network to be fully connected and can tolerate only a few seconds of partitioning.

As shown in this related review, that these protocols are based on the adopting real time vehicular traffic density estimation to improve the reliability and packet forwarding decisions. However, obtaining such estimates from interested region containing all road segments and junction requires additional transmissions that effect on the communication overhead and hence the probability of channel congestion in dense vehicular scenarios such as city area. Moreover, data forwarding decisions based on vehicular density also result in always routing packets over the road segments most prone to suffer the channel congestion and hence the latency increase. To deal with such problems, TASR suggest to obtain the vehicular density information and selection in advance for the ahead segments instead of the near segments which in result minimize the chances of local maxima. Furthermore, during the packet forwarding phase, TASR ignore the received packets which are not from the designated destination direction to control the channel congestion.

4.4 System Model

Envisioned a VANET environment that consist of roads with intersections, which is a typical scenario in urban areas. This section states the seven environmental conditions that are assumed in the design of the proposed TASR protocol.

1. It is assume that all vehicles are equipped with navigation systems that employ Global Positioning System (GPS) receivers or similar means of self-localization and On Board Units (OBU). These location aware vehicles obtain their geographical position information with the help of these untis. The vehicle communication has a range of at least 300 meters and each node can determine its position.

2. Each car features a wireless network interface for inter-vehicle communication that complies with standards such as 802.11p or Dedicated Short Range Communication (DSRC), and On-board Diagnostic Interface (ODI). The ODI acquires data from several mechanical and electronic sensors installed on the vehicle.

3. Nodes send Cooperative Awareness Messages (CAMs) — as for instance specified in the ETSI standard [ETSI, 2009] — enclosing their

own physical location, destination when applicable, current velocity and direction information. A packet header contains information such as a source ID, source location, packet generation time, expiration time and so forth.

4. Vehicles contain preloaded digital maps comprising street-level maps and traffic statistics (estimated traffic density, average vehicle speed on roads at different times of the day and traffic signal schedules at intersections). The payoff of such maps is discussed by [Yin et al., 2004].

5. A graph $G = \{V, E\}$ represents the current communication network topology with vertices V for vehicles and the edges E for communication channels between cars. The cars' initial positions are randomly selected with uniform distribution. Cars move with velocity v. Cars are neighbor and connected by edges when they are in communication range of each other. A path between two cars exist when they can reach one another via neighbors. Due to the nature of VANETs, paths must be continuously re-established with dynamic routing protocols.

6. The model region is constrained by a planer box. Vehicles are presented as mobile points and obstacles shielding communication as static square blocks. Figure 4.1 exemplarily shows a setting.

7. The Meeting Point (MP) is the estimated future position of the receiving car when it receives the data packet. Considered two cars, s a sender and d a receiver. The sender sends a data packet towards the receiver. Then, the MP is the position at the time the receiver receives the packet as shown in Figure 4.2. More formally, let there be intermediate node $Ni = (Ni_x, Ni_y)$ and the destination node $Nd = (Nd_x, Nd_y)$ with its future position $Pos_t(Ni)$ and $Pos_t(Nd)$ respectively after some time t. Let $\mathbb{Z}_t$ be the zone at time t, where the radio ranges of both Ni and Nd are expected to intersect and exchange the information. Thus $\mathbb{Z}_t = Pos_t(Ni) \cap Pos_t(Nd)$, if $\mathbb{Z}_t = \emptyset$, then the radio ranges of Ni and Nd do not intersect and thus the nodes are not (directly) connected, as follows;

$$Meeting\_Point_{Ni.Nd} = \begin{cases} 1 & \text{if } \mathbb{Z}_t \neq \emptyset \\ 0, & \text{otherwise} \end{cases}$$
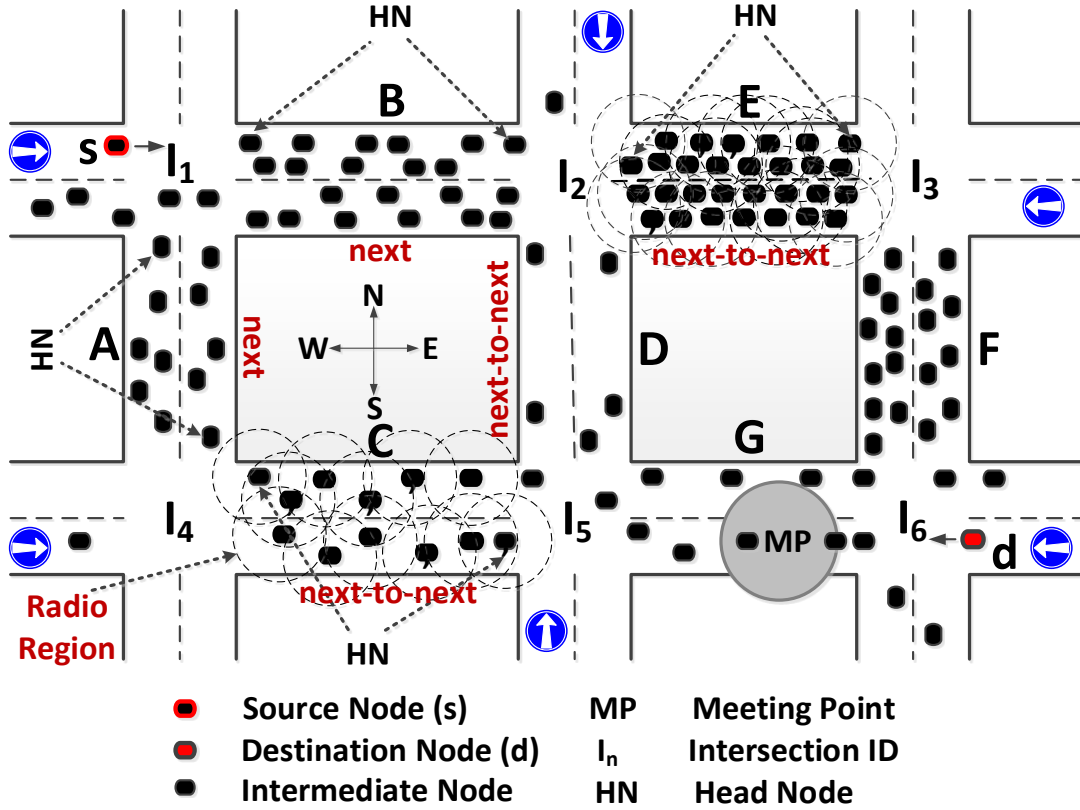
Figure 4.1: Trajectory model for the TASR protocol

4.5 Overview of the TASR Protocol

The Traffic Aware Segment-based Routing (TASR) protocol suggested herein exploits heuristics to select a robust communication path. Consider a VANET modeled as directed connectivity graph $G = \{V, E\}$ [Higaki, 2011] with V representing cars and E communication links. A time-dependent function indicates the nodes' mobility conditions $F(t) = f[x(i,t), y(i,t), z(i,t), v(i,t), \theta(i,t), \mathcal{R}_i]$ with $x(i,t), y(i,t), z(i,t)$ representing the position, $v(i,t)$ the velocity, $\theta(i,t)$ the movement direction and $\mathcal{R}_i$ is the unobstructed communication range of car i at time t.

TASR bases its routing decisions on traffic densities in road segments to guide a packet from one junction to the next junction. Specifically, TASR looks ahead not only to the next segment, but even to the segment after that, which is called Next-to-Next segment (N2N). Thus, TASR applies a look-ahead of depth two segments for routing.

In this thesis, the study was conducted to select N2N as it was expected that;

- The model to be viscous for a smaller look-ahead i.e. nearest segment vehicles are always connected, and

- Traffic to be high dynamic for a larger look-ahead.

Consider the source node s in Figure 4.1 sending a data packet to destination node d. To forward the data packets, s uses the estimated real-time information about the traffic on different segments. The three possible routes are;

1. $sBEFGd(s \rightarrow I_1 \rightarrow I_2 \rightarrow I_3 \rightarrow I_6 \rightarrow d)$,

2. $sBDGd(s \rightarrow I_1 \rightarrow I_2 \rightarrow I_5 \rightarrow d)$ and

3. $sACGd(s \rightarrow I_1 \rightarrow I_4 \rightarrow I_5 \rightarrow d)$.

The vehicular traffic densities on the different segments are $A = 11$, $B = 21$, $C = 14$, $D = 5$, $E = 29$, $F = 18$ and $G = 6$ vehicles per segment. The segment length is considered to exceed the communication range. TASR prioritizes segments with minimal latency, i.e. few vehicles, yet still with sufficient connectivity. Therefore, TASR selects $sACGd$ deterministically.
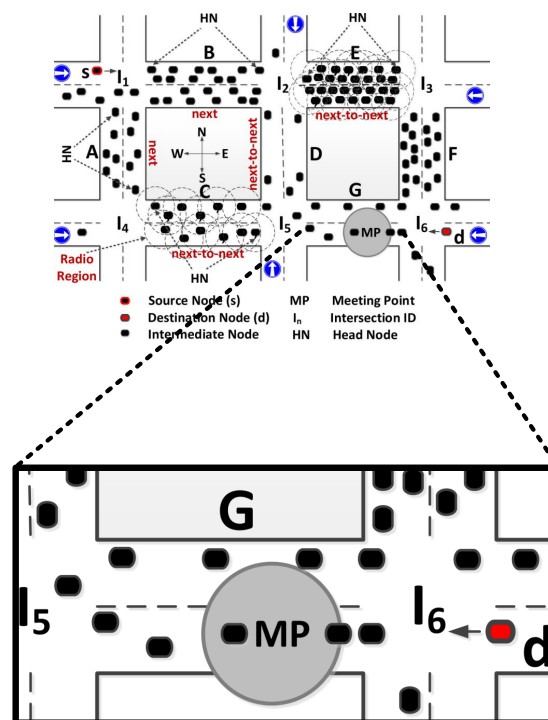
Figure 4.2: Meeting Point (MP).

4.6 Detailed TASR Protocol

Traffic Aware Segment-based Routing (TASR) is a novel segment-based geographical routing protocol aimed at finding a robust route that has minimum hop count and transmission delay while achieving a high packet delivery rate and overcoming the adverse effects of high mobility. To this end, a segment-based algorithm is developed to obtain real-time vehicular density information and based on this information it selects the Next-to-Next (N2N) segment. A connected road segment is a segment between two adjacent intersections with enough vehicular traffic to ensure network connectivity. Recent studies in VANETs multihop routing [Hinds et al., 2013] have shown that geographic routing with the help of GPS and digital maps ensures low end-to-end delay, low control overhead, and high end-to end packet delivery ratio.

Vehicles exchange packets using short-range wireless interfaces such as IEEE 802.11p and Dedicated Short Range Communication (DSRC). All these protocols assume that an efficient location management service is available to provide the source node with the destination location for routing. The proposed TASR protocol adopts related techniques to provide a robust route from source to destination nodes. The basic operation of TASR comprises two alternating phases:

- The first phase deals with selection of an appropriate segment, and

- Data packet forwarding takes place in the second phase.

4.6.1 Segment Selection

TASR selects segments dynamically to adapt to the real-time variation in vehicle densities. Each segment relies on two outermost nodes called Head Nodes (HNs). These nodes are responsible for collecting Estimated Connectivity Degree (ECD) and the traffic density information, and for disseminating messages into the segment or out of the segment respectively. The detailed segment selection procedure is shown in Algorithm 1.

A segment is fully connected when:

1. There is a path between its opposite two head nodes and

2. The head nodes are reachable from other road segments ,

which implies that each head node must be close to a junction as shown in the following Figure 4.3.
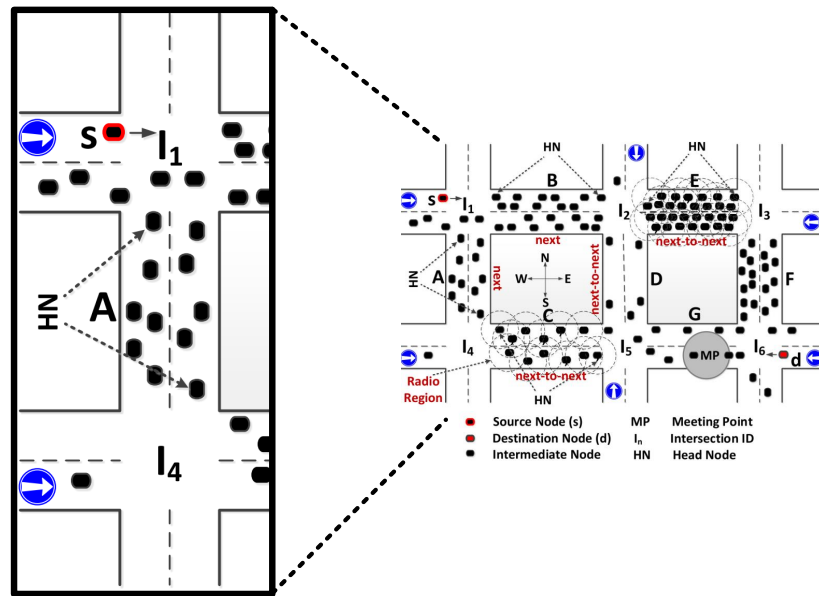
Figure 4.3: Positions of the Head Nodes (HNs) on the segment

4.6.1.1 Exchange Density Information

Vehicular state information is exchanged with other vehicles (within a certain transmission range) in order to maintain a neighbor tables helping the vehicles to identify the state vector information such as geographic position, speed, and direction of their neighboring nodes. These tables are updated periodically through HELLO messages. When a vehicle enters a road segment, it calculates the vehicles traffic density and their positions within that road segment.

By doing so, the vehicle becomes aware of the positions, and can declare itself as a Head Node (HN) if it finds itself at an ultimate position within the segment whether they are not unique. Each segment thus has two HNs at its both ends which declare and resign themselves autonomously.

An HN performs the following operations:

1. It accumulates the Segment Information (SI), i.e. the data about other cars, providing it to reachable HN neighbors.

2. For forwarding packets, the HN selects the Next-to-Next (N2N) segment based on retrieved information as discussed in Section 4.6.1.2.

An SI message comprises road ID, transmission time, transmission range and total density on the segment. Cars might slow down or stop thus maximizing chances for a better selection. Krauss formulation [Krauss et al., 1997] has been utilized to represent each vehicle individually by its state vector information (position, velocity, direction, etc.):

$$\textbf{Velocity-update: } V_{des} = min[V + a, V_{safe}, V_{max}]$$
$$V_{safe} = V + (d - V)/(\bar{V}/b)$$
$$V = \max[0, V_{des} - a\psi R]$$
$$\textbf{Motion-update: } x \leftarrow x + v$$

Here a denotes the maximum vehicle acceleration, b the maximum deceleration, ψ is the noise amplitude and R is a random number in $[0, 1]$. V is the ego-car speed, while $\bar{V}$ is the speed of the car ahead. This means that the drivers follow some kind of a stochastically perturbed maximum but safe velocity strategy. Moreover, if $\bar{V}$ is the velocity of the car ahead at time t then it can be further indicated with $\bar{V} = (V + \bar{V})/2$ the average of the vehicles velocities to determine the safe speed bound V_{safe}. Let us suppose that the frequency of HELLO beacons is related to the minimum contact duration. If the frequency of transmission is high, the time necessary for the information to reach the outer bounds of the geographic area is lower. For example, if the contact duration is 10 sec, the HELLO beacon will be transmitted every second.

4.6.1.2   Calculating the Estimated Connectivity Degree

The connectivity of nodes can be computed with the proposed novel metric named Estimated Connectivity Degree (ECD). It correlates with connection probability and thus characterizes the quality of each candidate path between the source and destination nodes. Furthermore, ECD is the segment-wise connectivity along a path between source and destination nodes. Two vehicles are considered to be connected if their distance is less than the vehicle transmission range R. A road segment is represented by a tuple of two end points as presented in [Higaki, 2011], i.e. $seg = (s, d^s), (s, d^d)$, where (s, d^s) shows the street crossing on one end of the road segment and (s, d^d) is the next street crossing on the other end. The segments in a grid area are represented via the junction coordinates as $N = \{((s_1, d_1^s), (s_1, d_1^d)) \ldots ((s_n, d_n^s), (s_n, d_n^d))\}$. For a segment, the estimated connectivity degree is computed as

$$ECD = 1 - \sum_{j=1}^{k} (-1)^{j-1} \binom{N_{nodes} - 1}{j} \left(1 - j\frac{\mathcal{R}}{L_{seg}}\right),$$

where $k = min \left\{ N_{nodes} - 1, \left[\frac{L_{seg}}{\mathcal{R}} \right] \right\}$, and where $\mathcal{R}$ is the transmission range of each node, L_{seg} is the length of each segment and N_{nodes} is the average number of vehicles on the road segment, while j represent the segment number. Through this formula the ECD for every N2N is computed, which then serves as a heuristic measure in segment selection. Consequently, based on this ECD, TASR deterministically selects the best option under the available N2N segment to route to the destination.

4.6.1.3 Determining Estimated Connectivity Degree (ECD)

Consider the Figure 4.1, there can be three cases for the path selection to forward the data packets from source node to destination node i.e.

1. $P_1 = sBEFGd(s \to I_1 \to I_2 \to I_3 \to I_6 \to d)$,

2. $P_2 = sBDGd(s \to I_1 \to I_2 \to I_5 \to d)$ and

3. $P_3 = sACGd(s \to I_1 \to I_4 \to I_5 \to d)$.

1. **Best case:** $P_1 = sBEFGd(s \to I_1 \to I_2 \to I_3 \to I_6 \to d)$

   In this case the distance between source and destination nodes is less than the radio range. Given that the radio range is $\mathcal{R}$, the connection probability of all nodes are accessible to each other node throughout the path $sBEFGd$, i.e. $X_{(s,d)} \leq \mathcal{R}$, is given by;
   $P_1 = P_{rob} \{X_{HN_A} \leq \mathcal{R}\} P_{rob} \{X_{HN_C} \leq \mathcal{R}\} P_{rob} \{X_{HN_G} \leq \mathcal{R}\}$
   So, HN_A has been taken as the distance between the two HNs on the same segment A. Let suppose that the overhead is 0 for the best path P_1, i.e. $K_{P_1} = 0$
   $$f_{K_{P_1}}(P_1) = \begin{cases} 1 & \text{if } K_{P_1} = 0 \\ 0, & \text{otherwise} \end{cases}$$

2. **Average case:** $P_2 = sBDGd(s \to I_1 \to I_2 \to I_5 \to d)$

   The distance between source and destination nodes through P_2 is less than the radio range $\mathcal{R}$, i.e.
   $X_{(s,d)} << \mathcal{R}$
   $K_{P_2} = \mathcal{R} + X_{(s,d)} + \Delta\mathcal{R} + \Delta X$
   $P_2 = P_{rob} \{X_{HN_B} >> \mathcal{R}\} P_{rob} \{X_{HN_E} >> \mathcal{R}\} P_{rob} \{X_{HN_F} >> \mathcal{R}\} P_{rob} \{X_{HN_G} >> \mathcal{R}\}$
   $$f_{K_{P_2}}(P_2) = \begin{cases} 1 & \text{if } K_{P_2} = (\mathcal{R} + X_{(s,d)} + \Delta\mathcal{R} + \Delta X)/2 \\ 0, & \text{otherwise} \end{cases}$$

3. **Worst case:** $P_3 = sACGd(s \to I_1 \to I_4 \to I_5 \to d)$

   The distance between source and destination nodes through P_3 is greater than the radio range $\mathcal{R}$, i.e.

   $X_{(s,d)} \geq \mathcal{R}$
   $K_{P_3} = X_{(s,d)}/2$

   $$P_3 = P_{rob}\left\{X_{HN_B} \leq \mathcal{R}\right\} P_{rob}\left\{X_{HN_D} > \mathcal{R}\right\} P_{rob}\left\{X_{HN_G} \leq \mathcal{R}\right\}$$

   $$f_{K_{P_3}}(P_3) = \begin{cases} 1 & \text{if } K_{P_3} = X_{(s,d)}/2 \\ 0, & \text{otherwise} \end{cases}$$

Algorithm 1 TASR segment selection

Notation:

s, d : ID's of the source and destination nodes
S_{next} : Next Segment
HNi : Head Nodes on segment i
$N2N_i$: Next to Next segment where $i = 1, 2, 3, ..., n$
ECD : Expected Connectivity Degree
S_s : Segment where s is located
S_d : Segment where d is located
RD : Route Discovery packet
n_i : Intermediate node

Upon request packet P from d:
s broadcast RD in S_s

   1: **if** $(n_i == d) \,\&\, n_i \in [S_s \vee S_{next}]$ **then**
   2:     Send packet $P \to d$
   3:     **break**
   4: **else**
   5:     **if** RD not seen before **then**
   6:         **if** $S_s \neq S_d$ **then**
   7:             Add $N2N_i$ segment to path
   8:             **if** HNi are connected on $N2N_i$ **then**
   9:                 calculate $\{ECD_1, ECD_2, ECD_3, ..., ECD_n\}$
   10:             **end if**
   11:             Select ECD s.t. $ECD = min\{ECD_{N2N_1}, ..., ECD_{N2N_m}\}$
   12:             Transmit packet $P \to n_i$ s.t. $n_i = d \vee n_i \in S_d$
   13:         **end if**
   14:     **end if**
   15: **end if**

4.6.1.4   Why is Route Selection Based on the ECD and the N2N Segment?

Analyzing the N2N segments provides a compromise between local greedy search (e.g. selecting the best next segment) and global planning (harvest

density information for all segments, then pursue global search). Using N2N does not come at a steep loss compared to global search due to the general confluence of road networks, which renders being caught in a blind route unlikely, while at the same time it is only moderately more expensive than local greedy search. N2N thus permits routing based on local information only while providing just enough look ahead. In highly dynamic city area network, the traffic varies rapidly over time, rendering global information harvesting infeasible within the short amount of time available for connection setup and communication. Table 4.1 exemplarily shows the densities for Figure 6.1. In this case the preferred N segment for the source node is A which depends on C and is suitable for route selection. Yet, density is not always proportional to likelihood. For instance, B is less suitable in the example than A as it relies on E which is more congested than C. Generally, to transmit the data packet to the nearest next segment (e.g. N) takes less time compare to far segment (e.g. N2N) and more far segment (e.g. N2N2N) and that is the reason if the variation take place in the node density of nearest or near segment but still have high probability to transmit the data, also this is the shortest way to MP.

Segment	Position	Density
A	N (next)	11
B	N (next)	21
C	N2N (next-to-next)	14
D	N2N (next-to-next)	5
E	N2N (next-to-next)	29
F	N2N2N (next-to-next-to-next)	18
G	N2N contains 'd'	6

Table 4.1: Segment identity and positions with related density

4.6.2 Data Forwarding Optimization

The TASR protocol builds routes using a Route Request/Route Reply (RREQ/RREP), send Data and receive Acknowledgment (Data/ACK) query cycle as shown in Figure 4.4. After selection of the Next-to-Next segment (N2N) as discussed in Section 4.6.1, data-packets are forwarded. In a segment, packets take the shortest multihop path. This attribute of robustness is essential for safety critical applications. A node receiving an RREQ packet returns an RREP packet if it has a route to the destination or is the destination itself; otherwise, it will rebroadcast the RREQ. Data packets are sent to the destination after the source node receives the RREP. In TASR, geographical forwarding is used to transfer data packets from source to

destination. The routing information is updated to ensure that the best route is selected. If a link breaks while the route is active, a route error (RERR) message is sent back to the source node. In case of sending back the RERR also fail and the sender did not receive any packet then the source node then re-initiates a route discovery process after certain period of time.

Furthermore, as the network becomes congested when the vehicles density increases, the overhead traffic from periodic HELLO messages negatively created an impact on the end-to-end data transfers. In previous works [B and Kung, 2000][Prosenjit et al., 2001][Fabian et al., 2003] on geographical or position based forwarding, each forwarding node picks the next hop using its list of neighbors and their state of vector information. In these forwarding strategies the next hop is chosen in such a way as to maximize the forwarding progress and always the selects nodes closest to the destination. This process continues until the packet reaches the destination. Therefore, to successfully choose next forwarding hops, it is vital for each en-route node to keep a precise neighbor list. However, due to the broadcasting a large overhead may be occurred. A solution is proposed to control the transmission overhead for each intermediate forwarder node to eliminate broadcasting in the whole transmission region. In this approach, the sender node broadcast the data packet only in the area of the transmission range ($R = \Pi r^2$) towards the destination and ignore the others. Furthermore, the proposed strategy also piggybacks its data on the IEEE 802.11 RTS/CTS frames [2], thus no transmission overhead arises. In IEEE 802.11 with Distributed Coordination Function (DCF) standard, the Request To Send (RTS) and Clear To Send (CTS) frames are used to address the hidden terminal problem that is inherent to wireless communication.

The proposed forwarding strategy within a road segment is illustrated in the following example Figure 4.4. In this example when S_i want to broadcast the packets to the intermediate nodes ($S_{i+1}, D_{i+1}, ...$), it broadcast only into the half of its transmission region oriented towards the designated direction, implying that nodes ignore the messages from the backside nodes. Once node S_i starts its transmission, it sends a very short RTS frame to the intended next hop D_i, including the transmission time of the follow-up data and acknowledgment frames. The receiver node D_i broadcasts a CTS message, which is received by all its nearby neighbors, once it receives the RTS with the needed channel clear time. In this example node S_i needs to broadcast and forward a data packet to the best next hop that is en-route to the destination. Node D_i hears the RTS frame, wherein the sender specified

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[2]Information in that regard is provided online, http://www.standards.ieee.org/about/get/802/802.11.html.

its own location along with state vector information of destination. Node D_i is selected as an intermediate forwarder node which is located on the transmission boundary [B and Kung, 2000]. After the link is established, the sender node forwards the Data and receives the acknowledgment (ACK). This example shows how this forwarding method can effectively choose the next hop to broadcast without any extra overhead. Moreover, the detailed steps are also presented in Algorithm 2.
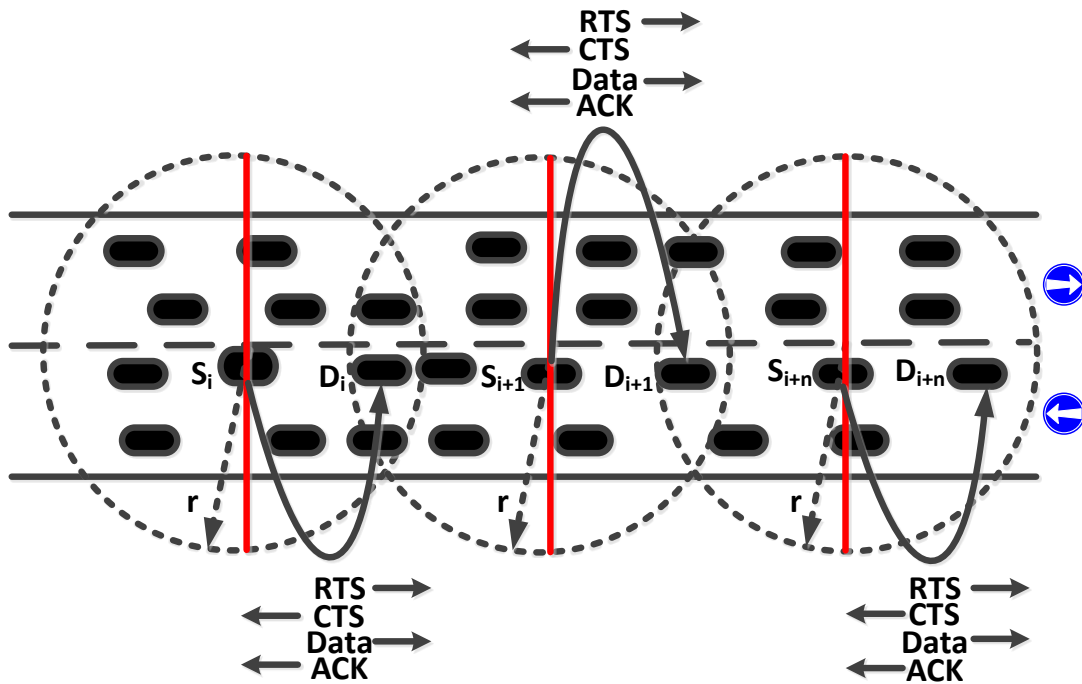

Figure 4.4: Data packets forwarding.

Algorithm 2 Data packets forwarding algorithm

 1: **procedure** DATA−FORWARDING
 2:     **for** each node $i \in n$ (where n=1, 2, 3,...,k) **do**
 3:         Broadcast HELLO message to its neighbor nodes i
 4:         let $i \in (\Pi \frac{r^2}{2})$
 5:         Select destination $D_i \in i$ (D_i is the best candidate)
 6:         Broadcast RTS from S_i (S_i is the source node)
 7:         Upon receiving CTS to S_i
 8:         Upon overhearing DATA, send back ACK
 9:     **end for**
10: **end procedure**

4.7 TASR Applications

Emergency vehicles like ambulances, fire brigade and police cars are special to respond on timely manner to an emergency situation. Thus, reaching

their destination of emergency situation as fast as possible is the important concern. Suppose an ambulance reaching the place of an accident place so ambulance going to the hospital carrying as injured person who needs medical assistance. In this case the ambulance need periodically updates about the road situation and also to update the hospital about the current status. During the contact with hospital, the ambulance can use the shortest and way to the hospital by utilising the TASR protocol scheme for message transmission. Another applications is also for the emergency vehicle i.e. fire brigade. When fire started, fire brigade which reach the place on timely. In concern to reach their destination faster as possible, the emergency vehicles define priority over the normal vehicles on the road and are often permitted by law to break conventional road rules in order to reach their destinations in the fastest possible time, such as driving through an intersection when the traffic signal light is red or over the speed limit. Although, it is possible that the emergency vehicle will reach to the destination when it is updated timely from the road situation. For example, if one road is highly congested in city area, then it need to change the route with the help of traffic information. A police car which wants to reach the place where a crime has just been announces. Also, if a violent car run away from the police can easily contact with their partner police. In all three situations, the timely required to reach their destination has create a great difference and also save human lives and time also.

4.8 Simulation Testbed

In engineering, ideas and concepts have to be validated by an at least prototypic implementation. Such a prototype may interface to a physical or just a sufficiently accurate virtual environment, and it may itself be a physical item, a mock-up, or a faithful simulation. Simulations have advantages that can hardly be replaced by testbed experiments. In simulations, different network scenarios can be constructed and amended according to the requirements. Using simulations, large sets of validation data can easily be collected. More importantly, a large scale network scenario can be modeled which would be very costly to set up in reality. But in order for the simulation to be indicative, the simulator had to be capable of simulating the vehicular networks and as providing control to the application to mimic the behavior of a human driving the vehicle. In this thesis different simulation frameworks are used as follows;

- **OMNeT++.** OMNeT++ is an extensible, modular, component-based C++ simulation library and framework with a generic architecture, pri-

marily for building network simulators [OMN,]. The term 'Network' is broadly used for the following;

– Wired and wireless Communication Network e.g. wireless ad-hoc networks

– Protocol modeling e.g. internet network protocols

– Multiprocessors and distributed hardware systems e.g. on-chip networks

These networks are provided by all modeling frameworks, developed as independent projects. OMNeT++ was developed at the Technical University of Budapest, Department of Telecommunication.

Basically, OMNeT++ is an open-source package and can be used either under the GNU general public license or under its own license which makes the software free for non-profit use such as academic, educational or research use [Varga, 2001]. OMNeT++ offers an Eclipse-based IDE, a geographical run-time environment and a host of other tools which can be integrated. Furthermore, there are extensions for real-time simulation, network emulation, database integration, Systems integration and several other functions. OMNeT++ tries to fill the gap between open-source, research and research-oriented simulation software such as Network Simulator (NS) [Bajaj et al., 1999] and a commercial OPNET [OPN,]. A simulation model in OMNeT++ consists of several architecture modules which are connected to each other and can transmit messages between each other as shown in Figure. 4.5. The smallest building block in a simulation model is called as Simple module. Such can be grouped into a Compound module and vice versa, where the number of hierarchy levels are not limited. Both Simple and Compound module access each other through Gates over connections that span between modules or directly through other destination's compound modules. OMNeT++ provides the tools required to describe the entire system structure by giving the following features;

– Hierarchically nested modules

– Flexible module parameters

– Network Description (NED) language which is high-level language, used to define the model structure of network topology

– Graphical and text editing of NED files

– Inter-module communication using messages through channels
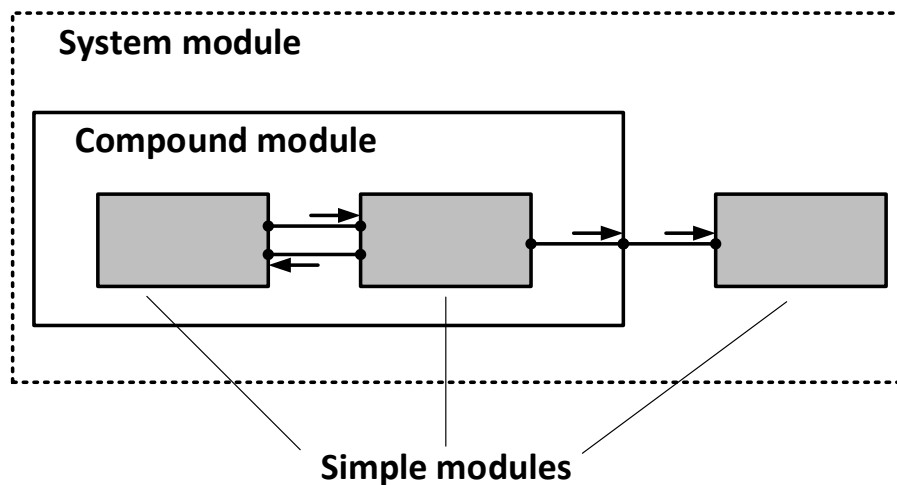
Figure 4.5: Model structure in OMNET++, Boxes represent simple modules (small boxes) and compound modules (contain two simple module), Arrows are connection which connecting the modules through gates.

Furthermore, an OMNeT++ simulation model consist of the following set of files;

- **.ned** files coded using the NED language which describe the connection structure and relative position among different modules. Also, values for different parameters related with simple modules can be defined here.

- **.msg** files are objects used for messages which contain the message structure and defining various message types with data fields. These messages are translated by OMNeT++ to C++ classes.

- **C++** source files are used for simple modules.

- An **.ini** file is used to specify modifiable parameters explicitly for all the modules involved at any level of the hierarchy.

- **SUMO.** SUMO means Simulation of Urban MObility [SUM,] and is a free and open traffic-simulation suite available since 2001. SUMO is a fast and portable microscopic road traffic simulator using C++ language developed by the Institute of Transportation Systems at German Aerospace Center (DLR). It is open source and licensed under the GPL and allows modeling of inter-modal traffic systems consisting of road vehicles (cars), public transport (buses) and pedestrians (bicycles). It models the mobility of these traffic systems in a microscopic way in which every vehicle, bus or pedestrian in the simulation is modeled

explicitly and has its own route. SUMO is a supporting tool which can handle different tasks such as route finding, visualization, network import and CO_2 emission calculation. Furthermore, it also counts the vehicle acceleration, deceleration and length variation between vehicle type. SUMO can be enhanced as well with other custom models and can provide various Application Programming Interfaces (APIs) to remotely control the simulation.

The simulation platform SUMO offers many features as follows:

- Microscopic simulation - consist of vehicles, pedestrians and public transport are modeled explicitly.

- Online interaction - Traffic Control Interface (TraCI) used for controlling the simulation.

- Simulation of multimodal traffic, e.g., vehicles (cars, truck and vans), public transport and pedestrians, each with unique characteristics like acceleration, declaration and maximum speed associated with them.

- Time schedules of traffic lights can be imported or generated automatically by SUMO.

- There are no restrictions and limitations in network size and number of simulated vehicles.

- Different scenario formats such as OpenStreetMap [OSM,], VISUM, VISSIM, NavTeq can be imported.

- SUMO is implemented in C++ and uses only portable libraries. Furthermore, all the configuration and data input such as route and network definitions are endorsed in the form of XML files.

SUMO has been used within several high quality projects for answering a large variety of research questions, as follows:

- The performance of traffic-light control which consists of the evaluation of modern algorithms up-to the evolution of weekly timing plans.

- It has also been investigated in choosing the vehicle route which include the new methods developments such as the evaluation of eco-aware routing based on pollutant emission and also to investigate on network-wide influences of autonomous route choice.

- SUMO was used to provide traffic forecasts for authorities of the city of Cologne, Germany, during the Pope's visit in 2005 and during the FIFA Word Cup 2006 in Germany.

- In the evaluation of the performance of GSM-based traffic surveillance, SUMO was used to simulate the in-vehicle telephony behavior and the associated mobility of phones.

- The V2X community also used SUMO for vehicle traces and evaluating applications in an online loop with help of a network simulator.

Furthermore, SUMO provides a suite of other supporting applications which helps import or generate the network and traffic for a simulations as follow:

- **SUMO:** command line simulation

- **GUISIM:** which provides simulation with a graphical user interface, enabling the user to observe the simulation in action.

- **NETCONVERT:** enables the user to import the road networks from different formats and generate a road network and road network that conforms with SUMO format. Specifically, NETCONVERT is used to support the scenario maps from OpenStreetMaps[OSM,] .

- **NETGEN:** used for the abstract networks generator.

- **OD2TRIPS:** converter from Origin-Destination (O/D) matrices to trips.

- **POLYCONVERT:** enables the user to import other components such as point of interest and buildings from OpenStreetMaps.

- **JTRROUTER:** generate routes based on turning ratios at intersections (junctions).

- **DUAROUTER:** generate routes based on a dynamic user assignment.

- **DFROUTER:** generate routes with use of detector data.

- **MAROUTER:** can be used for macroscopic user assignment based on capacity functions.

- **Veins.** Veins [Vei,] is an open source framework for running vehicular network simulations. This framework is the outcome of the Veins Research Project [Christoph et al., 2011] and was developed by the

team of Christoph Sommer, Falko Dressler and David Eckhoff at the Department of Computer Networks and Communication Systems, University of Erlangen, Germany. The purpose of the Veins development was to enable realistical simulation of Inter-Vehicle Communications (IVCs). This framework is based on two well-established simulators, namely OMNeT++, which is an event-based network simulator, and SUMO, which is a road traffic simulator [Sommer et al., 2008]. With the help of Veins, it cobines and extends these two simulators to offer a comprehensive suite of models for IVC simulation as shown in Figure refFigure:veins. Both simulators are bi-directionally coupled with the help of TraCI (Traffic Control Interface) and simulation is performed online.
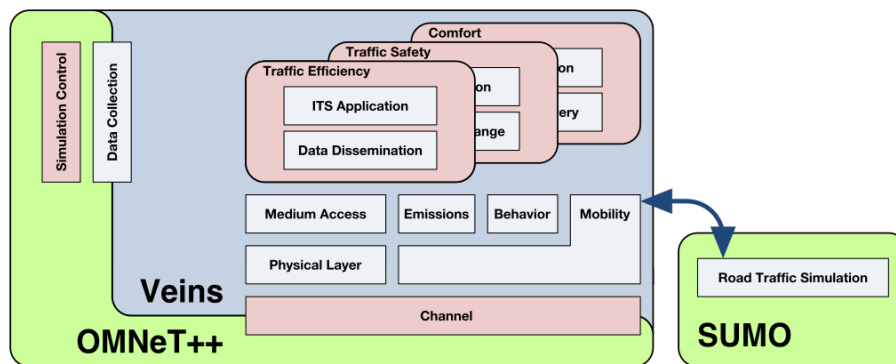
Figure 4.6: Architecture of Veins framework. (source:http://veins.car2x.org/)

This way, the influence of vehicular networks on road traffic can be modeled and the complex interactions between both domains examined. There are some important Veins features as follow:

– Veins is completely open source framework, hence it can be extended according to the requirements.

– Veins relies on trusted vehicular mobility models.

– Veins provides models for IEEE 802.11p and IEEE 1604 DSRC/WAVE network layers in complete details, e.g.

   ∗ Multi-channel operation

   ∗ Quality of Service (QoS) channel access

   ∗ Noise and interference effects

– Standalone workstation is enough for simulation, nut can be extended to computer clusters for improved performance and scalability.

– Veins also provides obstacle models which account for the shadow-ing effects caused by Non Line of Sight (NLoS) communication across buildings, big trucks and foliage, etc.

4.9   Performance Evaluation

This section empirically evaluates the performance of the proposed TASR protocol and compares it with elated protocols. The empirical evaluation has been implemented using the OMNeT++ 4.5 network simulator. The Simulator for Urban MObility 0.21.0 (SUMO) provided an environment for the co-simulation of traffic and the mobility of cars therein. The Veins 3.0 framework was employed to connect both as Section 4.8 discussed in detail. For the experiments, the test area is 2km×2km within the city of Oldenburg (Oldbg.), Germany, yielding the grid layout shown in Figure 4.7 is selected.

In the test area chosen, the relevant junctions and segments are marked as red circles and black lines, respectively. We realistically considered obstacles to exist between all segments that share no Line-Of-Sight (LOS). The initial positions and destinations of all vehicles are selected randomly. When the destination is reached, another destination is randomly selected. This procedure is repeated until the end of the simulation. The total number of nodes varies from 50 to 300 and the average node velocity is 40 km/h on average as shown in Table 6.1. Nakagami radio propagation model is used, which provides a general model of a radio channel with fading. The IEEE 802.11 DCF protocol is the MAC layer transmission protocol used and the shadowing propagation model reflected the dynamic channel conditions in VANETs.

Comparative protocols and metrics

The TASR performance is compared with different parameters against the performance of competing recent routing protocols such as MURU [Tsiachris et al., 2012] and VDLA [Li et al., 2014]. Section4.3 already briefly reviewed how each of these routing protocols operate. Furthermore, the comparison of these protocols with TASR on different perspectives are shown in the following Table 4.3.

The performance of these routing protocols was evaluated by varying constant bit rate (CBR), network densities and vehicles speed. The metrics used to assess the performance are the following:

• **Average data delivery ratio:** It is the ratio of actual packet delivered to total packets sent. The average delivery ratio shows the ability of
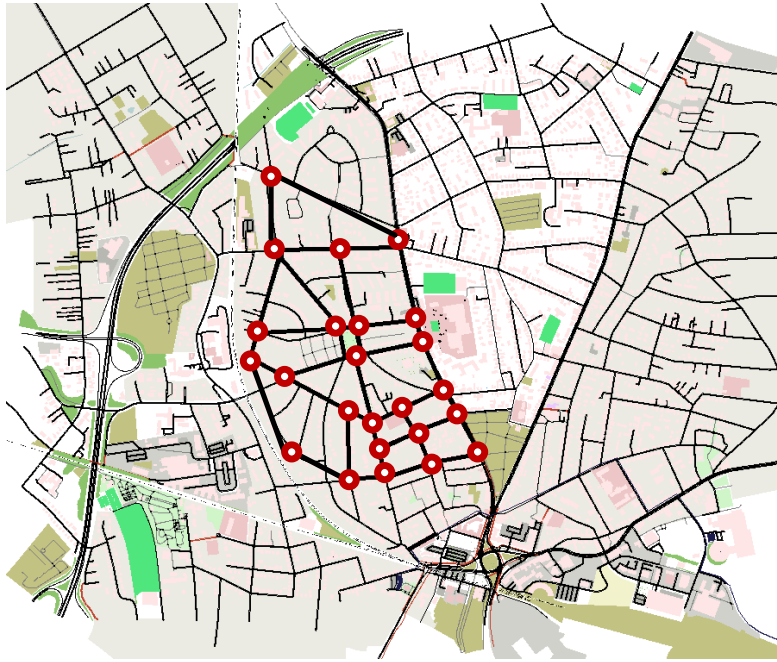
Figure 4.7: City of Oldenburg as a street graph in SUMO.

Parameter	Value
Simulation area	2km × 2km
Number of vehicles	50-300
Communication type	CBR
Simulation time	1000 sec
Average vehicle velocity	40 km/h
Transmission range	150 m
Normal packet size	512 Bytes
MAC protocol	802.11p
MAC data rate	6 Mb
Beacon interval	0.5 second
CBR rate	4 packet per second
Mobility model	Krauß model
Frequency	5.9 GHz

Table 4.2: Simulation setup.

the routing protocol to transfer data successfully end-to-end. A bigger value for the packet delivery ratio means a better performance of the protocol.

$$\sum \text{number of packet received} / \sum \text{number of packet send}$$

- **Average delay:** The average time taken by a data packet to arrive at the destination. It also includes the delay caused by the route discovery process and the queuing in data packet transmission. Only the data

Protocols	TASR	VDLA	MURU
Destination location method	Specialized	Specialized	Specialized
Forwarding strategy	Greedy forwarding based on ECD	Greedy forwarding	Lower EDD
Location service required	Yes	Yes	Yes
Recovery strategy	Recompute ECD value	Through recalculating the traffic density	No need
Path maintenance	Passively maintain, once disconnect start a new route	Unknown	Unknown
MAP required	Yes	Yes	Yes
Street aware	Yes	Yes	Yes
Vehicle-2-X	Yes	Yes	Yes
Scenario	Urban	Urban	Urban
Realistic traffic flow	Unknown	Unknown	Unknown

Table 4.3: Comparison between TASR, VDLA and MURU routing protocols.

packets that were successfully delivered to destinations are accounted for. A lower value of end to end delay designates a better performance of the protocol.

$$\sum (\text{arrival time - sending time})/\sum \text{number of connection}$$

- **Throughput:** It describes as the total number of received packets at the destination out of total transmitted packets. It is calculated as the the number of packets/bytes received per unit time.

$$\sum (\text{number of packet received at destination})*(\text{Packet size})/\sum \text{Simulation time}$$

Figures 4.8 shows an evaluation of the network connectivity against transmission range for different values of vehicle arrival rates. As is shown, the connectivity increases as transmission range increases. In addition, for a fixed transmission range it holds that the higher the density, the better the connectivity. It is because the higher the vehicle arrival rate which corresponds to a higher density on a road segment, which leads to higher number of average vehicle and thus the network connectivity better.

Figures 4.9 4.10 4.11 compare the Cumulative Distribution Function (CDF) of the probability of connection for 100, 200 and 300 nodes respectively. In these experiments, different scenarios were considered which represent morning rush hours (i.e. a dense network), noon time having intermediate density, and night time with low density. From these figures, it is noticed that TASR uses links with higher probability of connectivity (i.e., higher than 0.9) than the comparative protocols. Indeed, 76%, 87% and 92% of
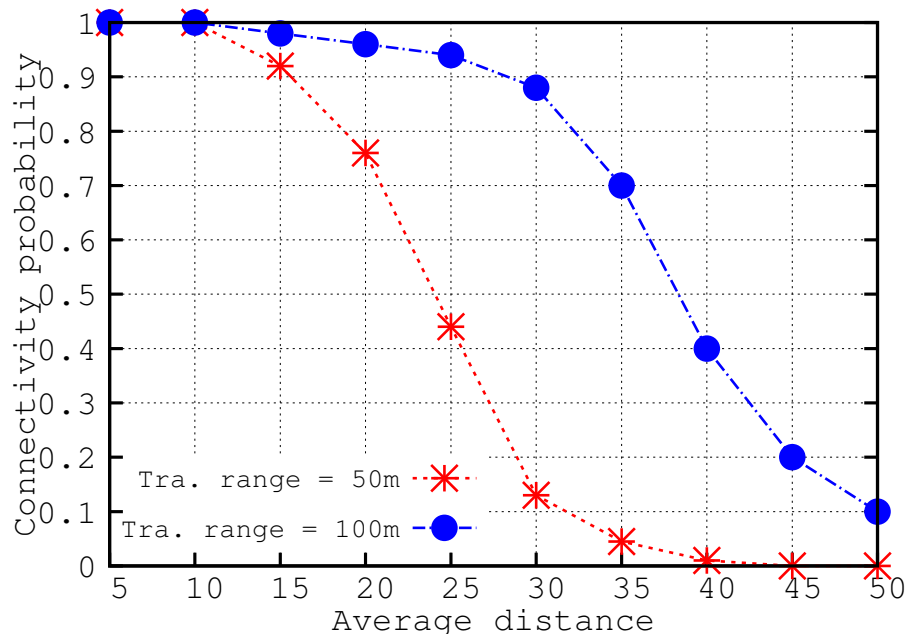
Figure 4.8: Connectivity probability vs. Average distance
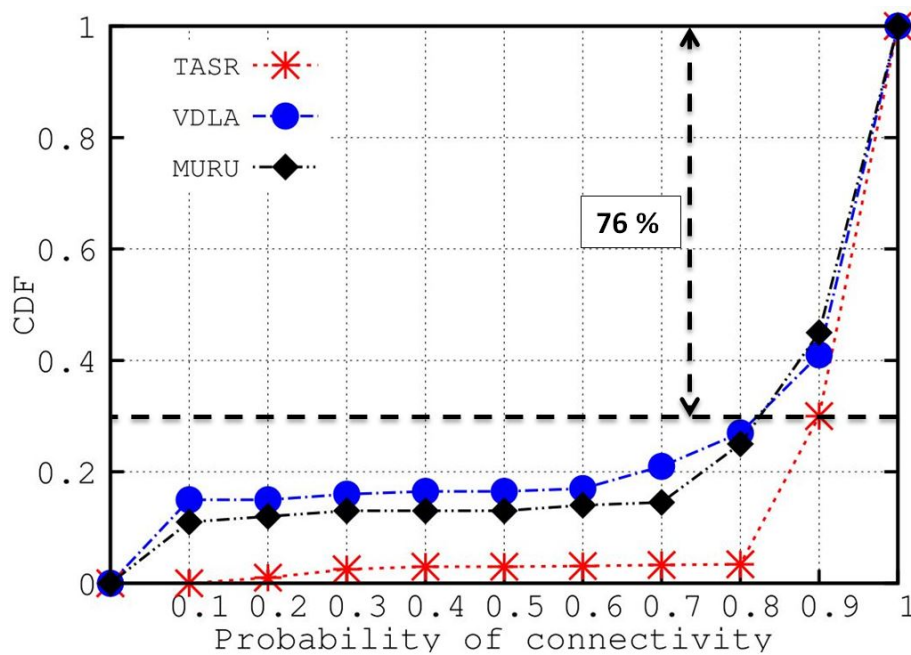
Figure 4.9: CDF vs. Probability of connectivity (100 nodes).

the links with $0.9 <$ Probability of connectivity < 1 are used by TASR for the 100, 200 and 300 nodes cases, respectively, against 69%, 77% and 79% for VDLA and 56%, 57% and 78% for MURU. According to these figures, when the density increase which influence on the connectivity probability and hence the CDF also increase. In other words, vehicles could make the connection when the inter-vehicle distance is less than the radio range. However, when the inter-vehicle distance is larger than radio range which in the case for low density, CDF begins to decrease. Therefore, it can be
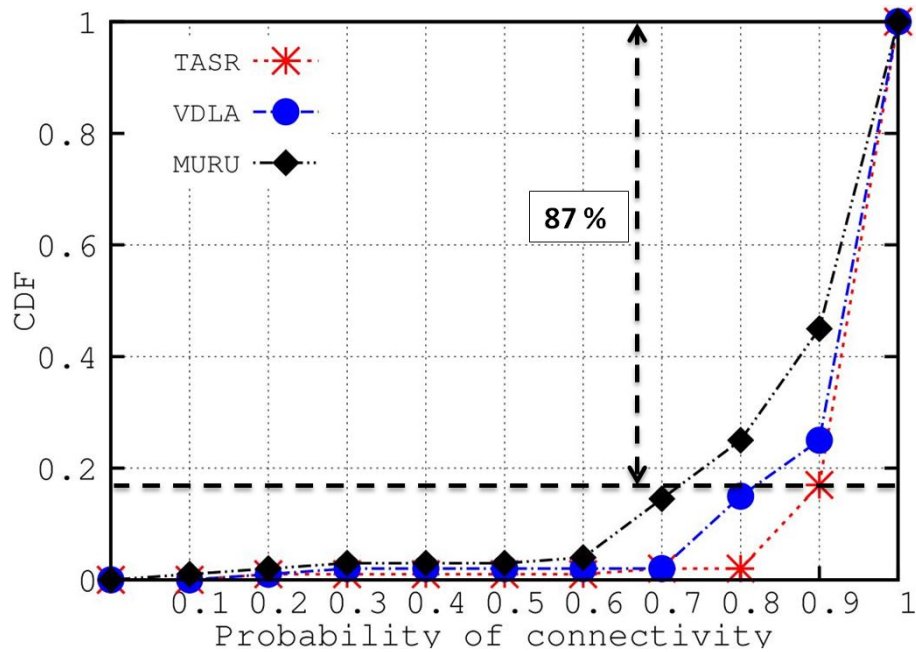
Figure 4.10: CDF vs. Probability of connectivity (200 nodes).
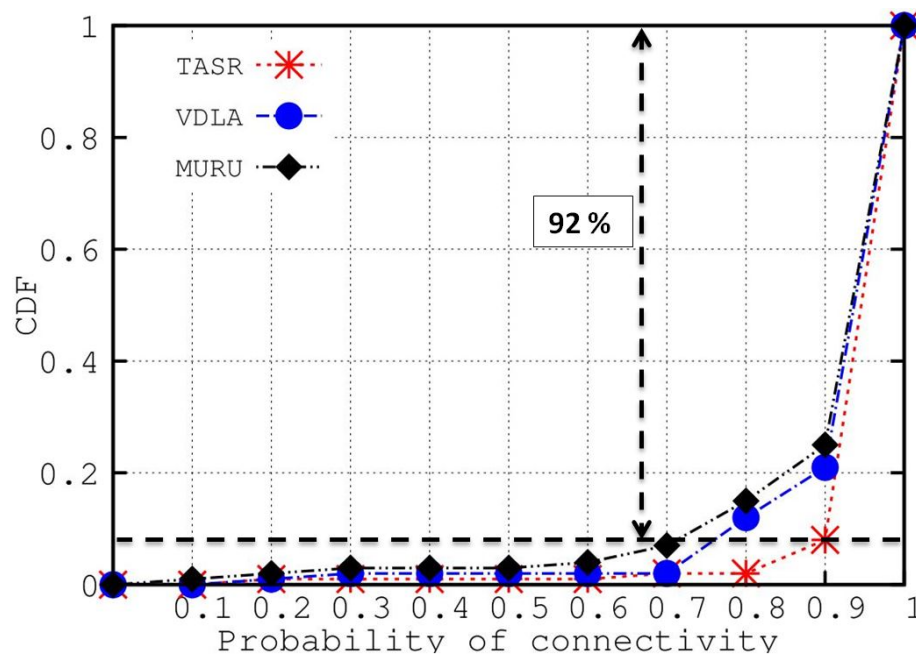
Figure 4.11: CDF vs. Probability of connectivity (300 nodes).

concluded that the available connectivity is mainly determined by the radio range.

Figure 4.12 shows the comparison of performance versus vehicle velocity. All simulated results show that average latency continues to increase as the vehicle speed becomes faster. As shown in the result, when the number of nodes are 100 and 200, the average latency increase slightly as compare with 300 deployed nodes. This result occurs because relay vehicles are selected with consideration of mobility patterns. Relative velocities among forward-
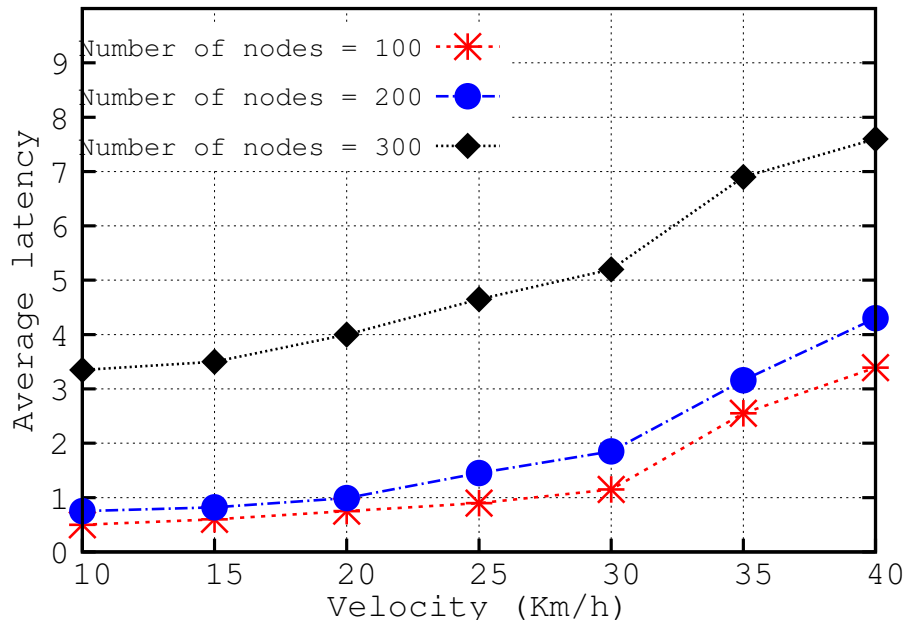
Figure 4.12: Packet average latency as a function of vehicle velocity.
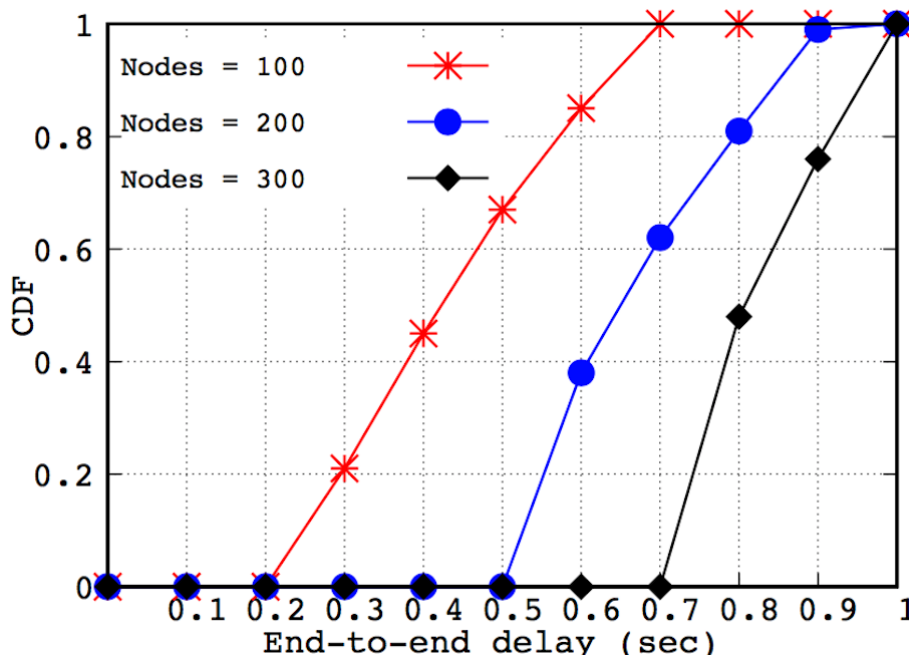
Figure 4.13: CDF of end-to-end delay vs Number of nodes.

ing vehicles are especially calculated and compared to avoid unstable packet delivery paths. When the vehicle velocity is lower than 30 m/s, average latency experiences no significant increase for 100 and 200 nodes. However, once the vehicle velocity is faster than 30 m/s, the latency grows rapidly; the faster the vehicle speed, the more packet the latency increases. The reason behind this is the short setup connection time i.e. during the transmission when the vehicles are moving with high speed, then chances to establish the connectivity is minimum due to the packet dropping. The findings of

this simulation confirm that vehicle velocity imposes a negative impact on packet delivery delay. Figure 4.13 shows analyzing the reliability of of the TASR in terms of CDF of the end-to-end delay versus the different number of nodes. From the figure, we notice that as the number of nodes increases, the CDF shift to the right side. The cause of this performance is due to the collisions among the packets, which increase with the increasing number of nodes in the network. It is very easy to understand at this point that the increasing number of collisions which cause from the high density result the increasing end-to-end delay experienced by the packets. In addition, the increasing number of nodes in network, in inter-vehicle communication is subjected to the phenomenon of congestion. In face, increasing the traffic up to a certain point where the network is no longer to handle the traffic then it enters into congestion. Higher the degree of congestion of the network, the greater will be the number of packets that never arrives at the destination.
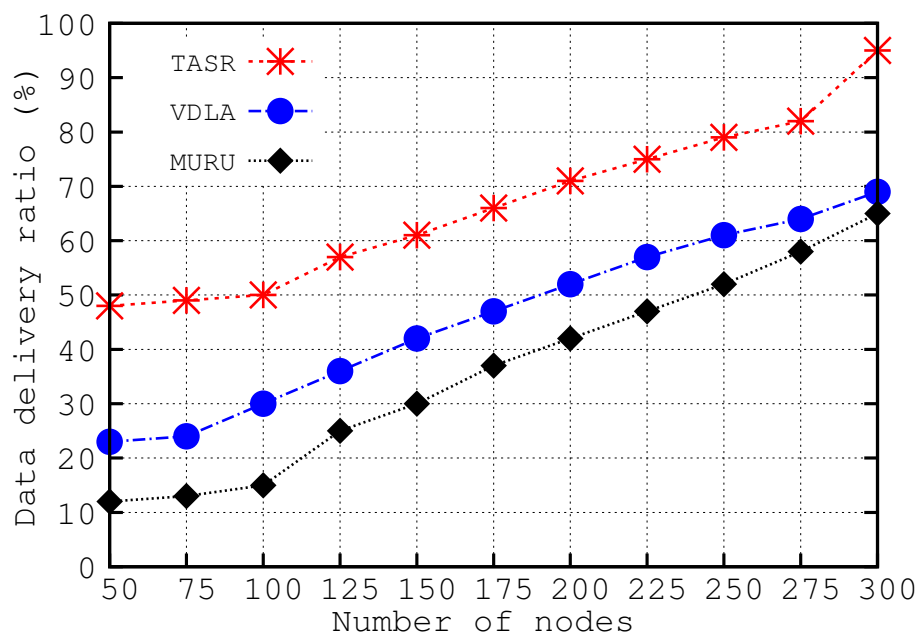
Figure 4.14: Data delivery ratio vs. Number of nodes

Figure 4.14 shows network performance in the terms of data delivery ratio. The average node speed, which is varied stochastically, and we change the number of nodes in the whole network. It is observed that TASR, which is based on Next-to-Next (N2N) selection, consistently improves over VDLA and MURU concerning packet delivery ratio, often by a substantial margin of approximately 28% and 32% respectively, especially when density reaches to 300. The reason behind this is the impact of congestion or contention for the shared medium between nodes caused by high node

density is a great problem in VANETs. In this scenario TASR outperforms its competitors in terms of packet delivery ratio which shows that TASR makes better use of network density. This is because when the number of nodes increases, the estimated network connectivity probability increases as well and so does the data delivery ratio.
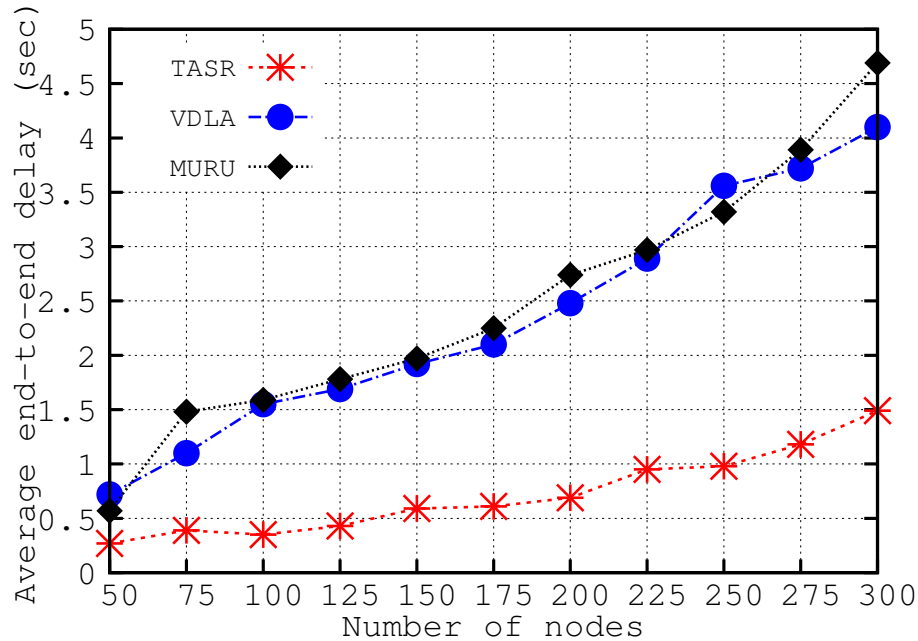
Figure 4.15: Average end-to-end delay vs. Number of nodes.

Figure 4.15 shows the advantages of TASR concerning delay over different densities. The end-to-end delay is effected by delivery ratio. TASR exhibits smaller end-to-end delay than VDLA and at all vehicular densities. This is because of decreasing the data-sending rate as redundant packets are effecitve when the vehicular density is high. The smallest delay reduction compared to MURU is 0.7 seconds at N=50 while the largest delay reduction is 4.7 seconds at N=300.

Figure 4.16 shows the overhead of routing protocols measured in the total number of routing packets sent. In this simulation the control packets are not considered. The reason is that the proposed TASR protocol is essentially a location-based protocol and it does not require any more control packets than other location based routing protocols. To keep up with VANETs mobility, data flooding may be required quite often and the routing overhead would lead to heavy congestion in the network. The proposed TASR protocol outperforms due to the suitable segment (N2N) selection avoiding the congested segment and thus a considerable difference can be seen compared with MURU and VDLA. Also, it is noted that when the network density is low, like 75∼100, both comparative protocols also give constant results, but
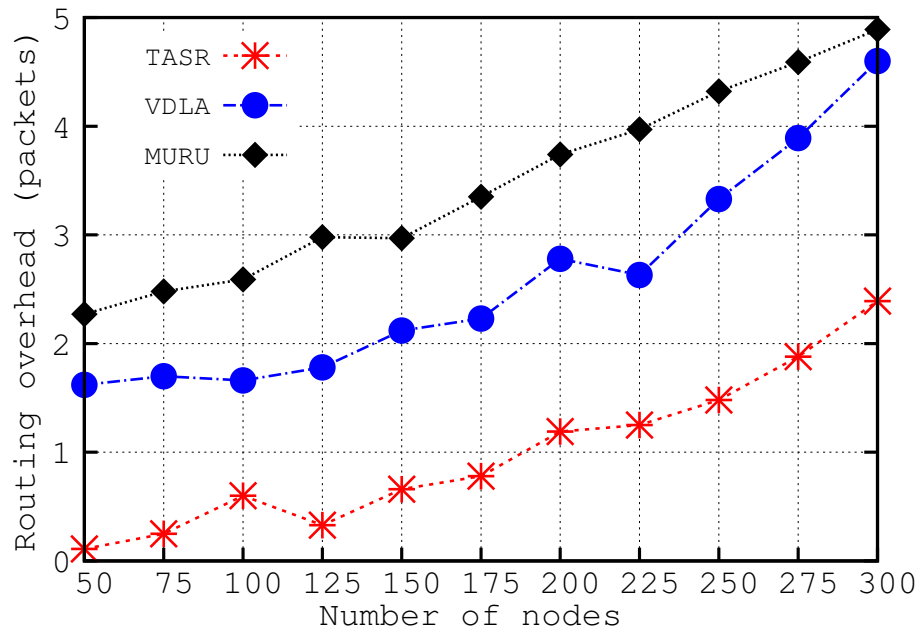
Figure 4.16: Routing overhead vs. Number of nodes

when the density increases then the overhead of both comparative routing protocols (VDLA and MURU) increases dramatically compared with TASR. In this experiment, the proposed novel metric ECD being utilized by TASR for selection of the N2N segment is demonstrated to dramatically improve delivery rate while minimizing the overhead, especially when the number of nodes increases. With the help of ECD, packet delivery ratio is enhanced rather than choosing randomly segment selection.
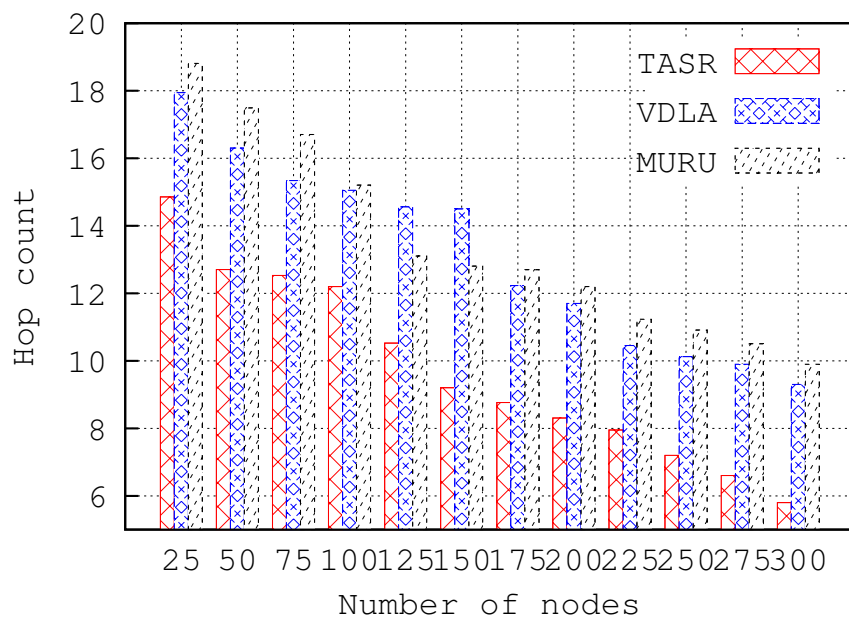
Figure 4.17: Hop count as a function of node density (300 nodes)

The result for the average hop count as a function of the number of nodes is presented in Figure 4.17. As depicted in the figure, TASR can achieve a lower average number of hops than other comparative protocols (VDLA and MURU). Even though, VDLA select the next junction before each junction but normally junction contain dense network and the data passes through multihop in the same region which creates latency. MURU also utilizes multihop strategy on the whole segments, which increases the hop count. However, in TASR the N2N segment is selected before each segment and the vehicle density is taken into consideration when it chooses the segment.
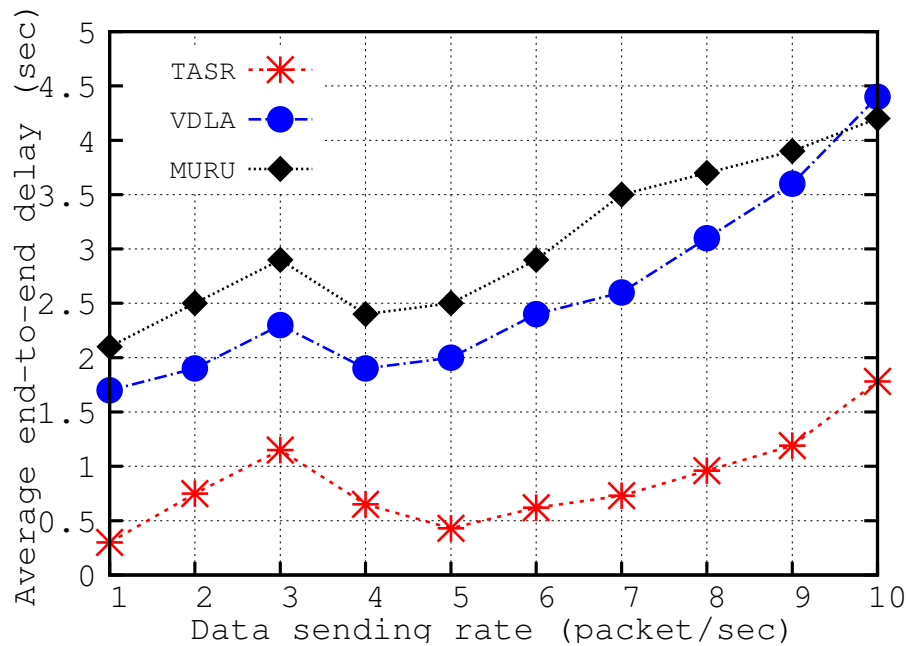
Figure 4.18: Average end-to-end delay as a function of the data sending rate (300 nodes)

Figure 4.18 shows that TASR has the smallest average end-to-end delay among the protocols evaluated. TASR perform better compared with MURU and VDLA due to the suitable nature of the scheme. In TASR the route is already chosen by the help of ECD. It is also observed that the average delay for TASR consistently remains less than 1 second while the average delay of MURU and VDLA increase dramatically. The reason behind this is the TASR look ahead and chosing the path which has maximum connectivity and minimum number of nodes.

Figure 4.19 and Figure 4.20 show how the minimum packet error rate and high data delivery ratio at different velocities. In Figure 4.19 the error rate is lower for TASR compared with its competitors. It is indicated that at low speed of less then or equal to 10 km/h, MURU has high error rate while TASR and VDLA have very similar error rates till the velocity of 20 km/h. In this case, both protocols can maintain connection for the mobile
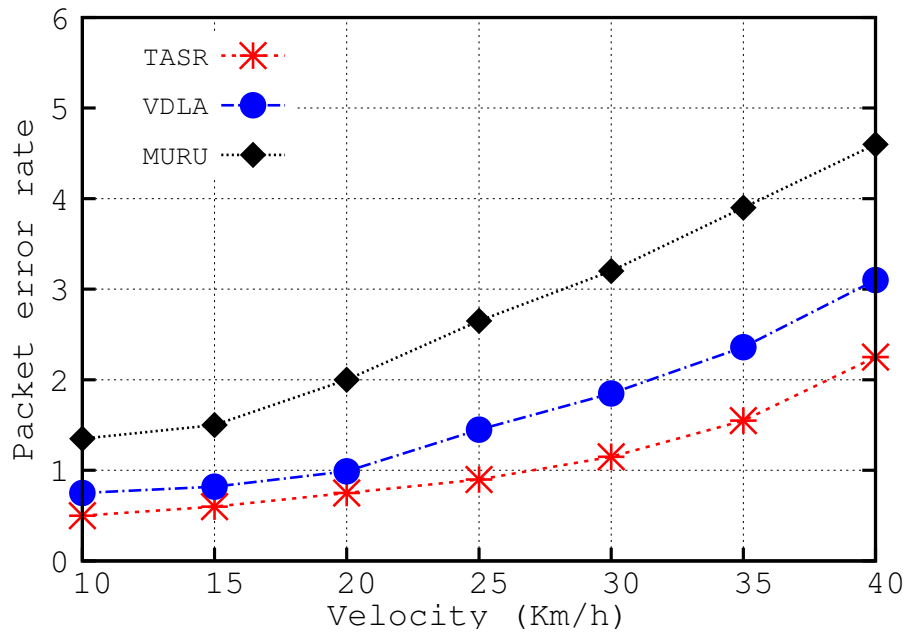
Figure 4.19: Data error rate as a function of vehicle velocity
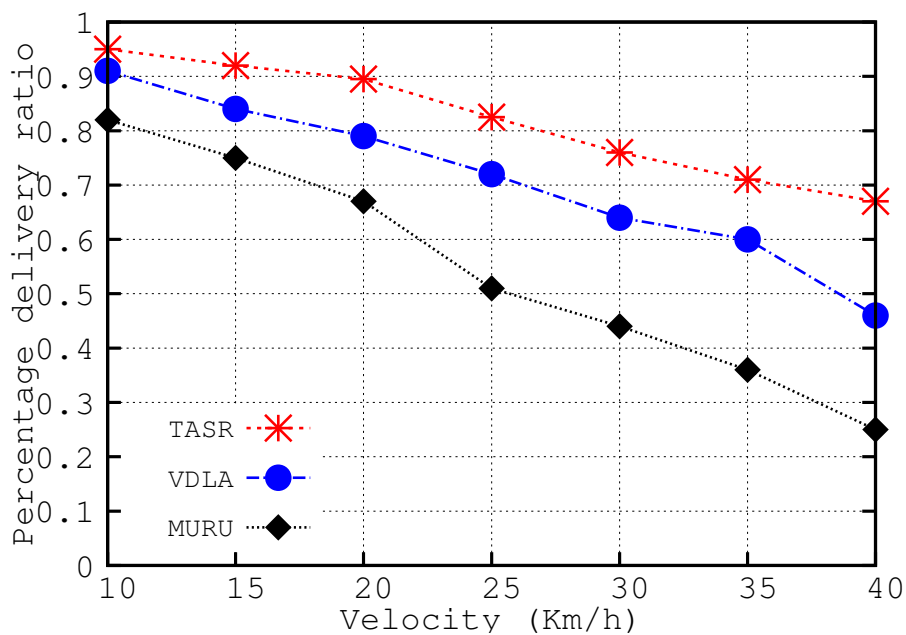
Figure 4.20: Data delivery ratio vs. Velocity

node with neighbors while traveling and losses are mainly due to packet collision. However, when the node speed increases this also has effect on the packet loss rate and data delivery ratio as shown in Figure 4.20. In contrast, TASR outperforms on low speed and high node speed as well. This indicates that our proposed protocol can reliably deliver data to intended recipients in a time-strict manner under varying traffic regimes without incurring into a high overhead in the network. As shown in Figure 4.21 and Figure 4.22, TASR protocol achieves the highest packet delivery ratio
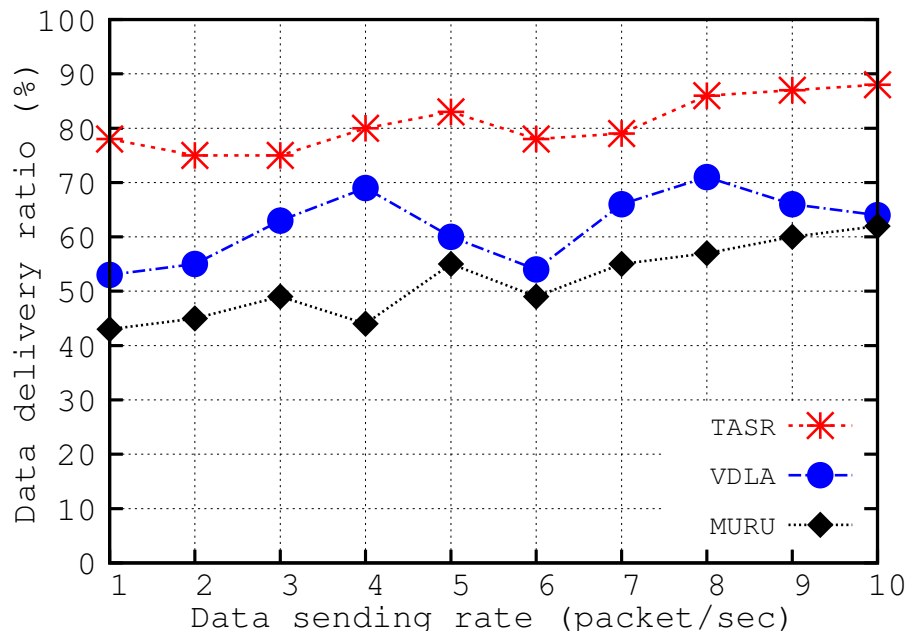
Figure 4.21: Data delivery ratio vs. Data sending rate
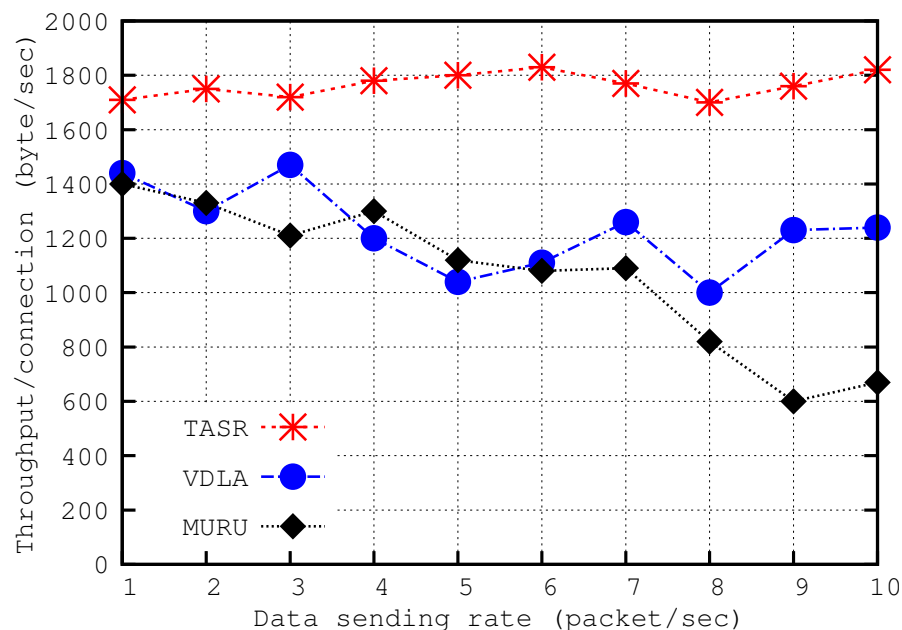
Figure 4.22: Throughput/connection vs. Data sending rate

and throughput compared with the others. There are two main reasons that TASR outperforms VDLA and MURU. First, the highest quality of the selected segment which guarantees a larger data delivery ratio while forwarding packets along the chosen path. Second, the next hop selection in TASR takes the entire path packet error into account while evaluating the neighbors. Therefore, the final packet error rate in TASR is much lower than comparative protocols.
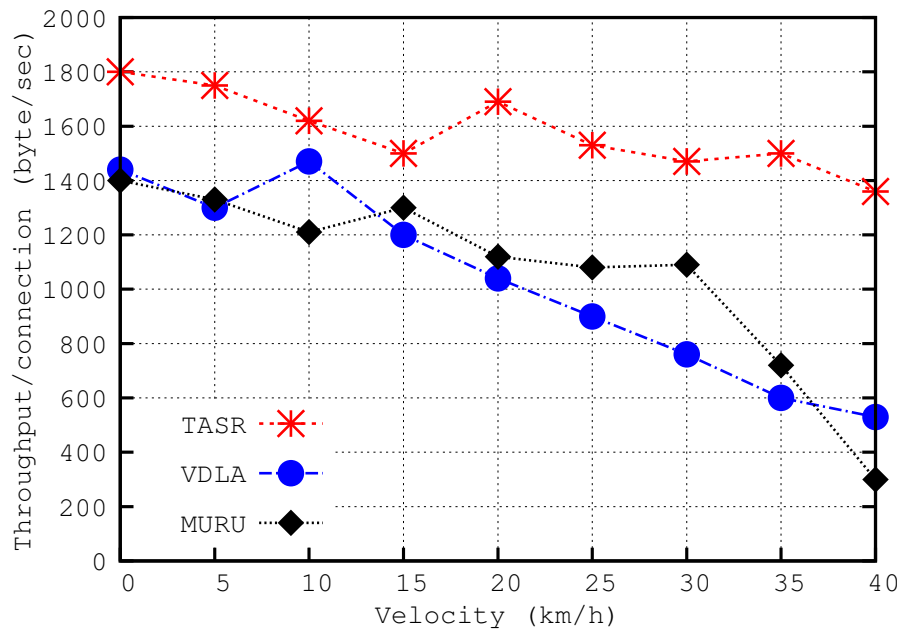
Figure 4.23: Throughput/connection vs. Velocity
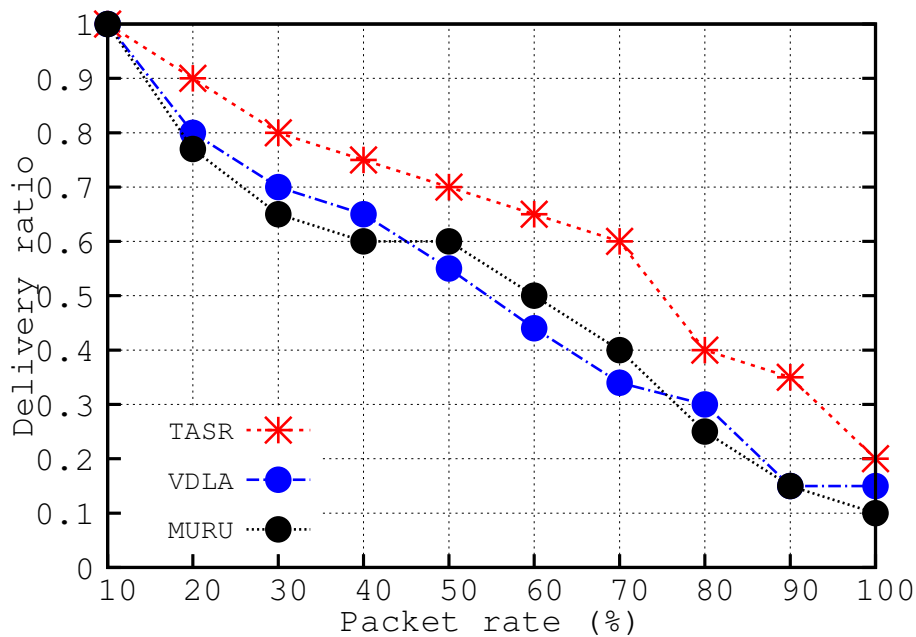
Figure 4.24: Delivery ratio vs. Data packet rate

Figure 4.23 shows the appropriate simulation result for how the throughput drops as cars accelerate, yet still leaving TASR at top. In this result the average TCP throughput connection is depicted as a function of node speed. At first, we notice that the throughput of all protocols clearly is stable when the node speed is low at 5∼15km/h. This behavior results from the network connectivity in the VANET. At lower node speed, the connectivity in the network is significantly better. Moreover, the result also may be subject to statistical fluctuation since communication partners are selected randomly.

At higher node speed, the throughput of both comparative protocols clearly declines because more and more vehicles have to share a common wireless channel and the routing overhead increases. Here TASR presses here its advantages of exchanging only small routing messages. TASR was able to cope best with the fast changing network topology and the high relative speeds of the vehicles. TASR was able to provide the highest throughput (up to 1749.85byte/sec at 20km/h) of all protocols, followed by VDLA. MURU's throughput decreases rapdily when the node speeds increase (from 1511.83byte/sec vs. 10km/h to 570.64byte/sec vs. 40km/h). Finally, we can see that VDLA only achieves an extremely low throughput of up to 353.22byte/sec when the node speed is 40km/h.

4.10 Chapter Summary

This chapter presented the TASR protocol for city-based environments that takes advantage of the road topology to improve the performance of routing in VANETs. The TASR protocol uses real-time vehicular traffic information to create road-based paths between end-points. The proposed protocol considers the segment-based selection based on vehicular traffic density. The road segment is chosen based on the proposed novel metric called Estimated Connectivity Degree (ECD). A modified geographical greedy forwarding algorithm is utilized to find forwarding nodes along the road segments that form these paths. Simulations were conducted using OMNeT++, SUMO and Veins frameworks. The TASR protocol showed superiority for all selected settings and outperformed existing approaches in terms of connection probability, average latency, average data delivery ratio, average end-to-end delay, throughput and packet error rate. The reason behind this is that TASR utilizes forwarding of data packets only along the segments, not across the segments and takes into account the real traffic on the road segments, which perform well in realistic vehicular environment in which line of sight does not exist because of buildings and other road characteristic such as dead end segments. Furthermore, the simulation results demonstrate that distributed applications that generate a moderate amount of data traffic can be successfully implemented in VANETs.

5. Cooperation and Network Coding (CNC) based MAC Protocol for VANETs

5.1 Introduction

Inter-Vehicular Communication (IVC) emerges as a promising system solution for future road communication scenarios. The mobile vehicles are expected to organize themselves locally in Vehicular Ad-hoc Networks (VANETs) without any pre-installed road side infrastructure. By utilizing such system, vehicles are expected to provide high bandwidth internet access to a large number of vehicles in a specific area [Toor et al., 2008]. Data broadcast is a major function in IVC, such as it is obligatory for the different software updates which may happen at the initial deployment and also for the maintenance period. It could be utilize for infotainment services such as audio and video files downloading. A key essential of these applications is to provide strictly guarantee of high Packet Delivery Ratio (PDR), which means that every concern node in the network has to download each bit

of the broadcasted file. In addition, such systems will enable the drivers to instantaneously obtain information about hazards and obstacles ahead resulting in improved automotive safety and better traffic flow [Tian et al., 2003] [Luo and Hubaux, 2004]. In this sense efficiency for data packet communication is an additional significant influence. Since the network may consists some other alternative normal unicast traffic at any time, then the broadcast applications should have good coexistence with these traffics. Also, it translates into consuming minimal amount of network bandwidth and disseminating the data file with low latency [Yang, 2011]. It is nontrivial to design an efficient and reliable broadcast protocols in wireless networks. The fundamental challenges come from the unreliable nature of the wireless links as discussed in [Zamalloa and Krishnamachari, 2007], which is due to packet losses caused by channel fading and interfacing hurdle.

In order to give guarantee for high PDR with those unreliable links, some earlier schemes employed Automatic Repeat Request (ARQ) technique, which demand the receiver node(s) to provide explicit feedback's of the data packet reception status to the source node [Pagani and Rossi, 1997] [Sobeih et al., 2004]. However, this will cause "ACK implosion" problem which may incur a large amount of redundant transmissions. ACK is an abbreviation of acknowledgment. Other proposed schemes such as [Roger, 1998] [Jörg et al., 1997] [Luigi and Lorenzo, 1998] combine ARQ together with Forward Error Correction (FEC) technique to reduce the transmission overhead while still guaranteeing high PDR. Yet, these different techniques still consider the wireless link as point-to-point connection, and neglect the real fact that wireless medium is broadcast in nature. This fact leads to the duplicate transmission at intermediate nodes, which are not efficient enough and satisfiable.

To cope these challenges, Network Coding (NC) has been proposed as an effective technique to increase the network bandwidth-efficiency [Fragouli et al., 2006]. In contrast to FEC, NC gives intermediate nodes the ability of randomly encoding different data packets received preciously into one output data packet. Thus, although multiple intermediate nodes may receive the same data packet, they will broadcast different re-coded data packets that are linearly independent with each other with high probability. Each of these re-coded packets can benefit other nodes that overhear it, which avoids the duplicate transmissions. Theoretical analysis has demonstrated that NC is able to approach the multicast and broadcast capacity in multihop wireless networks [Adjih et al., 2007] [Lun et al., 2008]. Due to the high complexity of implementing network coding, practical NC-based broadcast

schemes have also been proposed [Fragouli et al., 2006] [Park et al., 2006] [Chachulski et al., 2007] [Hou et al., 2008] [Dimitrios et al., 2008] [Yunfeng et al., 2008].

The remainder of this chapter is organized as follows: Section 5.2 motivated the study. The related work with the definitions of different techniques and selected literature are presented in 5.3. Section 5.4 presents the problem statement and Section 5.5 describes the proposed MAC protocol along with contention window adjustment scheme. Evaluation results are shown in Section 5.6 and the chapter concludes in Section 5.7.

5.2 Motivation

The aim of communication networks are to deliver information in the form of data packets between end-to-end nodes. Classically the data packets are delivered by employing paths for unicast and trees for multicast connections. Moreover, unicast path is, when the data packet is routed over a designated path, each intermediate node receive over its incoming edges and forward the data packets through its outgoing edges. On the otherside, multicast connection over tree, the intermediate nodes may duplicate packets and forward them to several outgoing edges. Furthermore, the basic Network Coding (NC) approach [Ahlswede et al., 2000] permits the intermediate nodes to process and generate new data packets by the received data packets on their incoming edges. This technique provides various benefits, such as a) an increase in connection throughput b) an improvement in connection reliability and c) network robustness etc.

5.3 Related Work

In this section a brief overview of IEEE 802.11 DCF has been explained, network coding technique is presented in detail along with an example and their advantages. Also, cooperative communication is discussed along with the selected literature.

5.3.1 Overview of IEEE 802.11 DCF

The IEEE 802.11 Distributed Coordination Function (DCF) is a non-persistent Carrier Sense Multiple Access (CSMA) scheme. During the transmission, the node exist in the network contend for channel access. A node willing to transmit the data have to sense the channel and then transmit in case if the channel is free for some period of time as defined by DCF Inter-frame

Space (DIFS). In case, the channel is busy then node defers the transmission and wait for a certain period of time before the next attempt on the channel. There are two transmission modes in IEEE 802.11 DCF: Two-way handshake which is the basic access mode and four-way handshake which is based on Request-to-Send and Clear-to-Send (RTS/CTS) [Gast, 2002]. The basic mode is used for small size data packet transmission to send the data packets and receive the acknowledgment (ACK). The second mode is consist of four way handshake. This mode is to be utilized in ad-hoc networks where the sizes of data packets are large.The RTS/CTS exchanges serve two purposes: to coordinate the data packet transfer between sender node and receiver node, also announce the duration of the data packet transfer to neighbor nodes of the sender and receiver nodes. A sender node transmit a RTS packet to intended receiver, if the RTS successfully received then CTS packet is send back to the sender node from the receiver node after a specific period of time which is called Short Inter Frame Space (SIFS), which indicate that a data packet can be transmitted. A collision in the channel can be occur due to the absence of CTS packet on the sender end. If a collision occurs, the sender node goes into backoff as show in the following equation.

$$Backoff\_Time = rand[0, CW\_current] \times Slot\_Time \qquad (5.1)$$

The Backoff_Time is defined as the product of a random integer between 0 and Contention Window (CW) size, and the Slot_time is a predefined time interval. CW starts at a predefined CW_min which have the default value of 31 in IEEE 802.11. CW double every time on a collision until it reaches a predefined CW_max which have the default value of 1023 in IEEE 802.11. This process is called exponential backoff scheme as the increase in CW is an exponential. When the backoff timer reduce to 0 then the willing node attempt to retransmit the RTS packet. Upon a successful transmission contention window is reset to CW_min. If the sender node receive the correct CTS packet, the receiver sends an ACK packet back to the sender. If the sender fails to receive the ACK, it assumes the data packet is lost and retransmits the RTC as shown in Figure 5.1.

IEEE 802.11 DCF is fully distributed scheme and every wireless node operated without the acknowledgment of the conditions of other nodes. In this chapter 5, the proposed protocol also try to maintain the characteristics of IEEE 802.11 DCF.
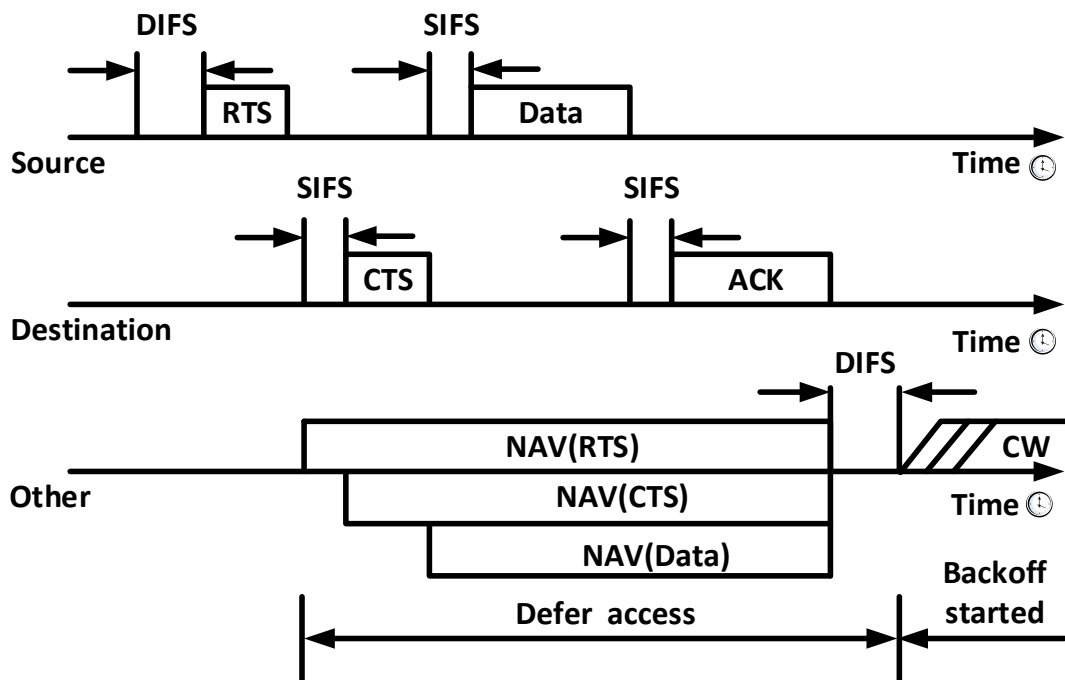
Figure 5.1: IEEE 802.11 DCF Four-way handshake.

5.3.2 Network Coding

The concept of Network Coding (NC) was first introduced by R. W. Yeung and Z. Zhang in 1999 as an alternative to data packets routing technique [Ahlswede et al., 2000]. NC can be defined as, a method of optimizing the flow of digital data in a network by transmitting digital evidence about messages and effective way to make optimal utilization of the available network resources. The "digital evidence" is itself a composite of two or more messages. Such as, when the bits of digital evidence arrive at the destination, the transmitted message is deduced rather than directly reassembled. Furthermore, the authors of [Jun and Jean-Pierre, 2004] reported that by using NC in the intermediate nodes, a sender node can transmit and communicate for the information to a set of receiver nodes based on the broadcast capacity of the network. Also, the advantages of NC has been addressed in [Li et al., 2003] [Ho et al., 2003]. In simple words network coding can be define as "information can operated and processed on in network, not just relayed and transported". NC allows to capture advantage of the broadcasting capabilities of the shared wireless medium to provide benefits in terms of bandwidth, transmission power and delay. Clearly to give assurance the deployment of such techniques, the demanded processing of data within the network requires to obtain low complexity and power con-

sumption. Wireless networks are natural for implementing network coding because the performance of traditional wireless ad-hoc routing is imperfect over unreliable channel. NC is less prone and susceptible to a single point of failure. In a traditional packet-switched network, data flows is defined as the discrete "pieces" transmuting from the source node to the destination node such as corpuscles in the bloodstream flows. During the transmission phase at the transmitting station the outgoing message is fragmented into multiple packets, each of which contains some of the message data intact. It is not obligatory at all that the data packets must be travel along the same identical route but they all eventually need to arrive at the same destination point. At the destination point after receiving the information packets, the computer then reassembles them into the original message. The major issue with this method is that when the overall network traffic volume is enough high which create bottlenecks in the network, resulting in long delays. Packets tend to bunch up at certain nodes, sometimes in excess of the nodes ability to process them. Other routes and nodes may remain under-utilized.

NC is an elegant and novel technique introduced at the turn of the millennium to improve network throughput and performance. In NC, communication devices such as routers and switches are substitute by other devices called 'Coders'. Instead of directing the packets toward their ultimate destination like blood cells through a system of arteries, the coders transmit meta-data in the form of digital evidence about the message along multiple paths simultaneously. Conversely, the meta-data arriving from two or more sources may be combined into a single packet [Net,]. The type of distribution method can be effectively useful to increase the network capacity by minimizing the number of severity of bottleneck issues. Furthermore, the improvement is most pronounced when network traffic volume is near the maximum capacity achievable with traditional routing method. When a receiver node has enough digital evidence, it can compute the intended information in form of data packets. Even though, if some packets on the specified routes are lost or mutilated then the original message gets through if the received digital evidence is sufficient. More over, the data does not depend just only on one transmitted message but also on the contents of other messages that happen to be sharing the route at the time of transmission. For this reason, NC is more resistant to hacking, eavesdropping and other forms of attack than traditional data transmission. The extent of throughput improvement that network coding can provide depends on the network topology and on the frequency and severity of bottlenecks. In no event does network coding reduce the throughput compared with the

routing method. Network coding may prove especially useful in multicast networks, wireless sensor networks, digital file distribution and peer-to-peer file sharing [Net,].

Much work in network coding has concentrated around a particular form of network coding such as random linear network coding. Random linear network coding was introduced in [Jain et al., 2003] as a simple and randomized coding method that maintains "a vector of coefficients for each of the source processes", which is "updated by each coding node". In other words, random linear network coding requires messages being communicated through the network to be accompanied by some degree of extra information–in this case a vector of coefficients. In today's communication networks, there is a type of network that is widely-used which can easily accommodates such extra information. Moreover, it consists of error-free links when the packet are transmitted in the networks. Along with data packets, such extra information or additional side information can be placed in packet headers and certainly placing side information in packet headers is common practice today such as sequence numbers are often placed in packet headers to keep track of order. Another common definition of NC is, coding at a node in a packet network where data is divided into small packets and network coding is applied to the contents of packets. More generally, coding above the physical layer [Ho and Lun, 2008].

5.3.2.1 Network Coding Motivating Example

In the following network example Figure 5.2 taken from [Ho and Lun, 2008], each arc represents a directed link that is capable of carrying a single packet reliably. There are two packets i.e. b_1 and b_2 present at the source node s, and we wish to communicate the contents of these two packets to both of the sink nodes i.e. t_1 and t_2. Furthermore, node s is a multicast source that has the packets b_1 and b_2, and there are two destinations terminals i.e. t_1 and t_2, each of which is interested in receiving both b_1 and b_2. Without network coding nodes 3 and 4 will be the bottleneck link and will have to alternate between sending b_1 and b_2. However, if the netwrok coding technique is utilize and it can allow node 3 to merge b_1 and b_2, the multicast capacity will achieved and link 3 and 4 will bot be a bottleneck. In this case node t_2 recovers b_1 by XORing b_2 with $b_1 \oplus b_2$, and similarly t_1 recovers b_2 by XORing b_1 with $b_1 \oplus b_2$.

5.3.2.2 Advantages of Network Coding

In the following section, Figure 5.3 and Figure 5.6 from [Sprintson, 2010] are taken to demonstrate the advantages of network coding technique.
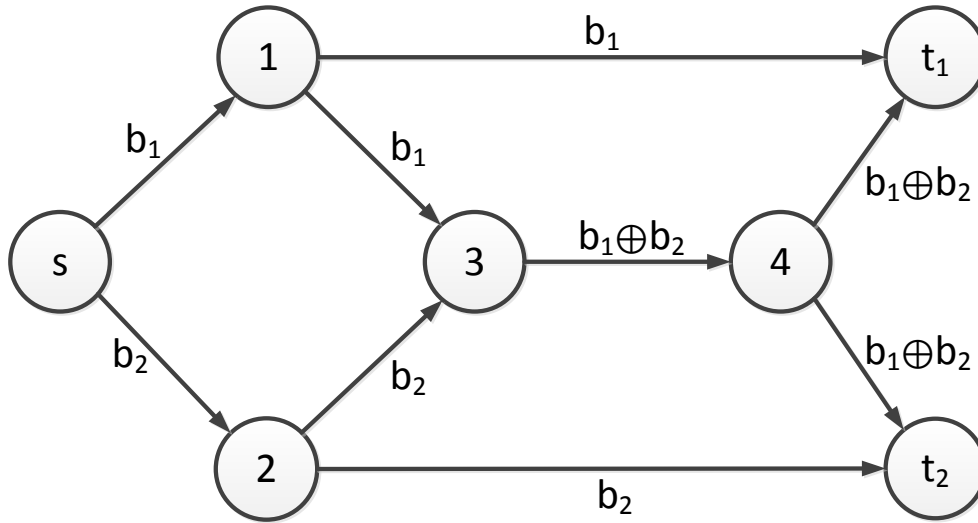
Figure 5.2: A butterfly network example for multicast capacity achievement.

- **Throughput:** The most conventional utility of NC is throughput in-
  creasing. This throughput benefit is achieved by using packet trans-
  missions more efficiently and reliably i.e. , by communicating more
  information with fewer packet transmissions. Consider the network il-
  lustrated in Figure 5.3a. The network includes two information source
  nodes i.e., s_1 and s_2 and two destination nodes i.e. t_1 and t_2. Con-
  sider that all edges of the network are of unit capacity, i.e., each edge
  can transmit one data packet per time unit. The capacitated network
  that is consider, the desired multicast connection can be established
  only if one the intermediate nodes breaks from the traditional routing
  paradigm of packet networks where intermediate nodes are allowed
  only to make copies of received packets for output and perform coding
  operation. It takes two received packets and generate a new packet
  by taking the binary sum or XOR mechanism of the two packets and
  the outputs the resulting packet. While network coding can increase
  throughput for multicast in a wire-line network, its throughput bene-
  fits are not limited to multicast or to wire-line networks. Figure 5.3b
  and Figure 5.3c share the bottleneck edge v_1 and v_2. Figure 5.3d
  shows that this conflict can be resolved by employing the network cod-
  ing technique which is highly beneficial for high network throughput
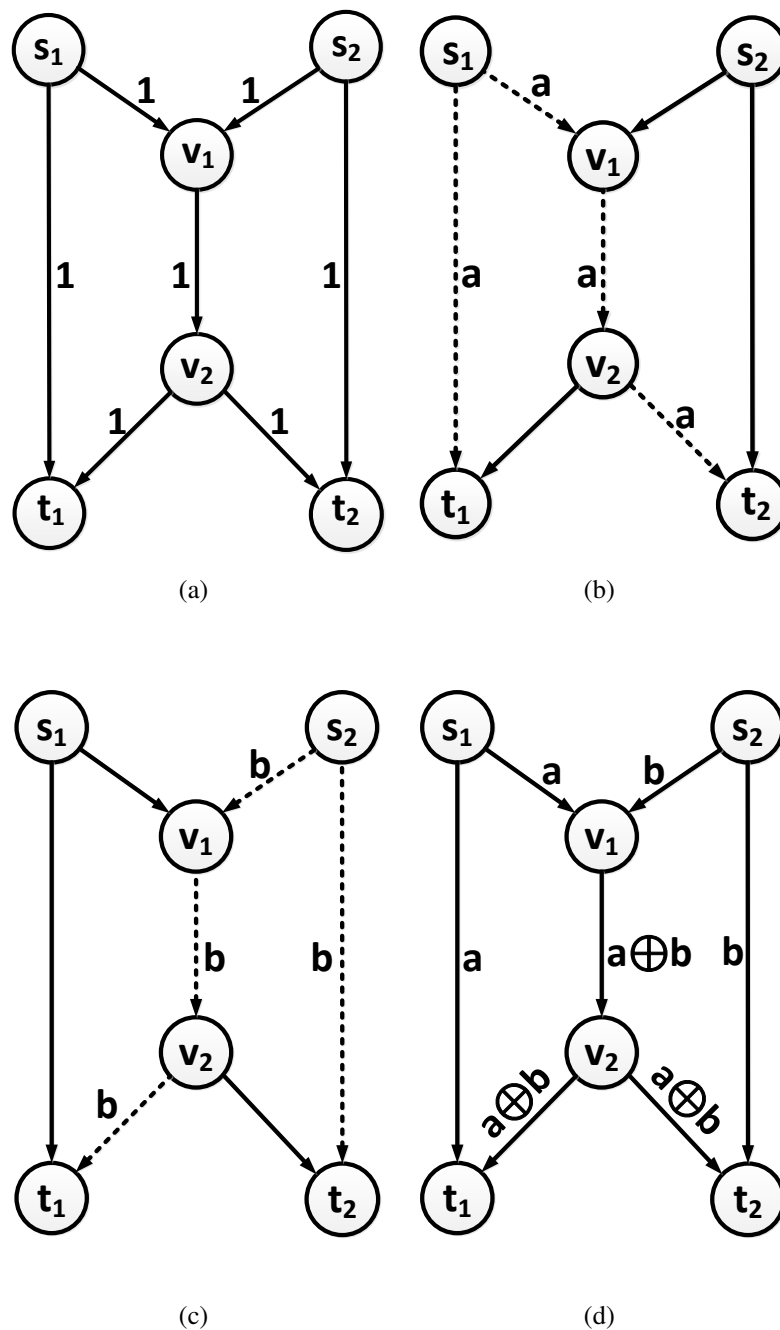 achievement.

Figure 5.3: Basic network coding example (source:[Sprintson, 2010])

- **Robustness:** Robustness in terms of packet loss and link failure is another important network property. Packet loss arises for various reasons in networks, which include buffer overflow, link outage and packets collision. There are a number of ways to deal with such losses. Perhaps the most straightforward, which is the mechanism used by the transmission control protocol (TCP), is to set up a system of acknowledgments, where packet received by sink are acknowledged by a message sent back to the source and if the source does not receive

the acknowledgment for a particular packet. It retransmits the packet. An alternative method that is sometimes used is channel coding or, more specifically, erasure coding (which introduce a degree of redundancy). Besides robustness against the packet losses, network coding is also useful for protection from non-ergodic link failures. Live path protection, where a primary and a backup flow are transmitted for each connection, allows very fast recovery from link failures, since rerouting is not required. By allowing sharing of network resources among different flows, network coding can improve resource usage. For a single multicast session, there exists, for any set of failure patterns from which recovery is possible with arbitrary rerouting, a static network coding solution that allows recovery from any failure pattern in the set [Ho et al., 2003].

- **Minimize number of transmissions:** The network coding technique can also be employed to minimize the number of transmission in wireless network [Wu et al., 2005]. For example, considering a simple wireless network as depicted in Figure 5.4. The network contains two nodes s_1 and s_2 that want to exchange packets through an intermediate relay node v. More specifically, Figure 5.4 also shows in detail the minimization number of transmission. A node s_1 needs to send packet a to s_2 and node s_2 needs to send packet b to s_1 which shows a traditional routing scheme that requires four transmissions. Utilizing NC scheme in which the intermediate node v first obtains two packets, a and b from s_1 and s_2 and then generates a new packet, $a \oplus b$ and broadcasts it to both s_1 and s_2. This scheme requires only three transmissions. The example shows that through network coding technique the transmission can be conveniently minimized.

- **Complexity:** In some cases, although optimal routing schemes may be able to achieve similar performance compare to NC but the optimal routing solution is difficult to achieve. For instance, minimum-cost sub-graph selection for multicast routing involves Steiner trees, where a Steiner tree is a tree that connects the source node with the destination terminal nodes and may include any number of other nodes. This mechanism is more complex even in a centralized setting while the corresponding problem with network coding is a linear optimization that admits low-complexity distributed solutions [Erez and Feder, 2004] [Ho et al., 2003] [Li et al., 2003].
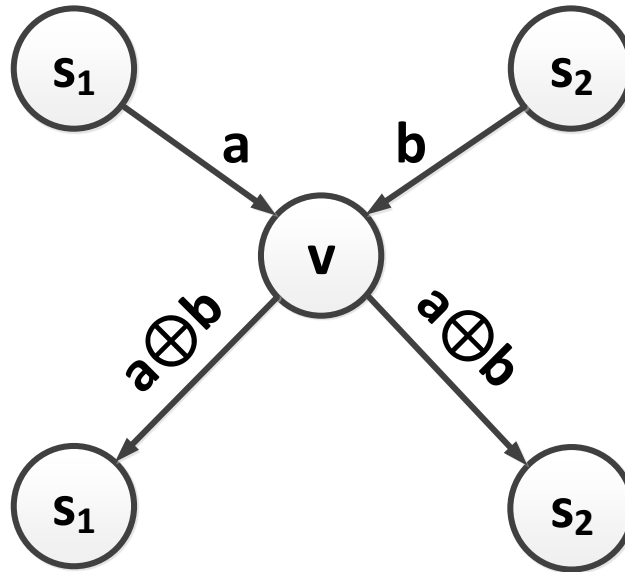
Figure 5.4: A modified butterfly network example for transmission minimization.

- **Security:** From a security standpoint, network coding can offer both benefits and drawbacks. Consider again the butterfly network example Figure 5.2. Suppose an adversary manages to obtain only the packet $b_1 \oplus b_2$. With the packet $b_1 \oplus b_2$ alone, the adversary cannot obtain either b_1 or b_2; thus we have a possible mechanism for secure communication. In this instance, network coding offers a security benefit. Alternatively, suppose that node 3 is a malicious node that does not send out $b_1 \oplus b_2$, but rather a packet masquerading as $b_1 \oplus b_2$. Because packets are coded rather than routed, such tampering of packets is more difficult to detect. In this instance, network coding results in a potential security drawback.

- **Delay minimization:** The network coding can also be useful for minimizing the delay of data delivery from the source node to the terminal nodes [Chou and Wu, 2007]. Considering an example as illustrated in Figure 5.5a, where each edge is transmitting one packet per time unit and even the delay for each edge is also the same i.e., one packet per time unit. The Figure 5.5b and Figure 5.5c show two edge-disjoint Steiner trees that connect source node with other connected nodes v_1, v_2 and node t. However, one of the trees is of depth three, and in result v_1 will receive the packet after three time units. The Figure Figure 5.5c proof that with the help of network coding, the delay is minimize upto two units time.
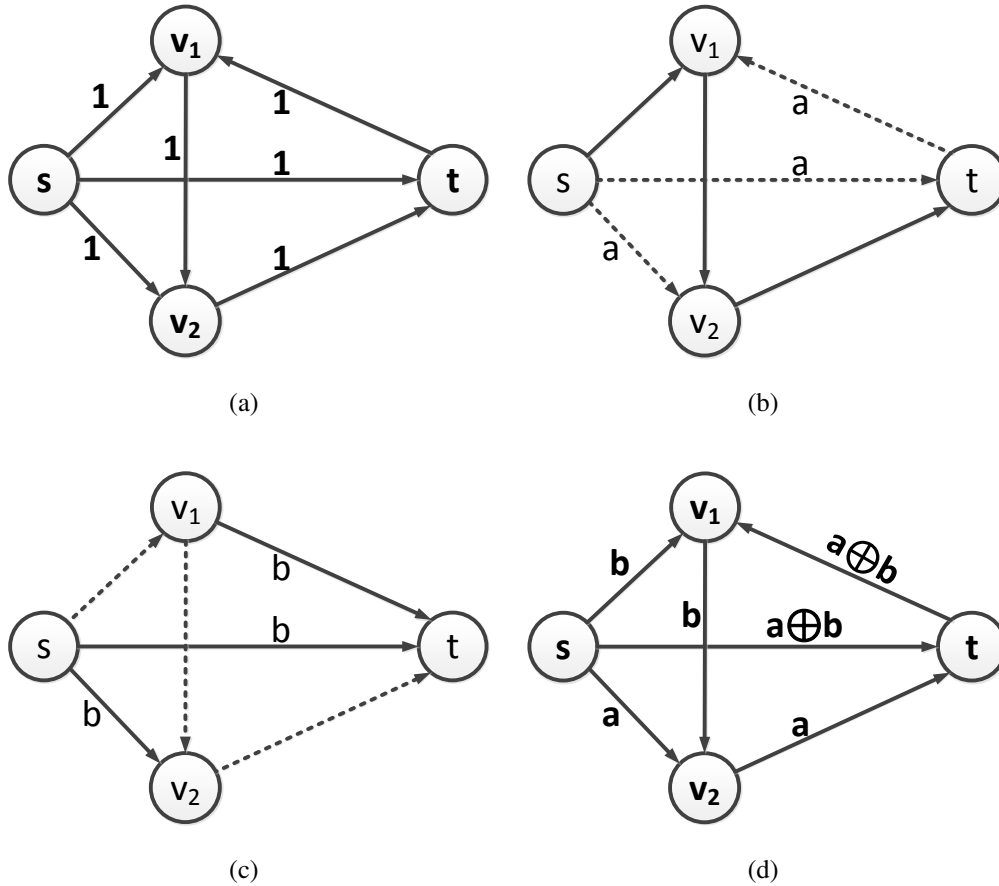
Figure 5.5: Delay minimization with network coding technique.

5.3.3 Cooperative Communication

Cooperative communications helps in improving the system reliability. Several cooperative signaling or relaying methods have been studied and evolved them in different techniques such as Amplify and Forward (AF) [Hunter and Nosratinia, 2002], Decode and Forward (DF) [Sendonaris et al., 2003] and Coded Cooperation (CC) [Hunter and Nosratinia, 2006]. These well known techniques are depicted in the following Figure 5.6.

The standard method of communication is transmitting the information from sender to the receiver. In Amplify and Forward (AF) as shown in 5.6a, the source node transmit the same information to both relay node and destination node during the first time slot. In the second time slot, the destination receives another set of signals which is; one from the source node and the other from is an amplified version of the signal in the first time slot. After receiving all these information, the destination node apply Maximum Ratio Combining (MRC) to decode the combined signal by match filtering. The relay node receives the

information signal appended by the channel and noise. In the final step, it is then amplified and sent to the destination node which is the combination of the input signal convolved with the channel gain and Additive While Gaussian Noise (AWGN). AF is very easy to implement while there is no possibility for decoding errors. The major disadvantage of this technique is that the noise also amplified at relay node.

In Decode and Forward (DF) as shown in 5.6b, relay node receives signals from the source node and check for the error. The information is then re-encoded and transmit to the destination. The destination node estimate the information signal by employing MRC. The relay node can either decode the entire signal or perform symbol-by-symbol decoding [Laneman et al., 2004]. The relay node decodes the received signal, the noise which is introduced in the information signal should be removed prior to decoding. Otherwise, it is more likely that the original signal could be corrupted. After that, the destination node must decode the information signal completely which should be completely aware about both decoding techniques. In real time environment, there is less certainty that the decoded signal sent from the relay would again be noise affected. As Nicholas Laneman have shown in [Laneman, 2002] that the decode and forward method fails to attain full spatial diversity. Also it is proved that the outage probability is inversely proportional to the Signal-to-Noise Ratio (SNR), i.e., the outage probability reduces at the same as the SNR rises and vice versa.

Wireless communications systems have a broadcast nature through the use of omnidirectional transmission antennas, enabling several nodes possibly including the destination to receive multiple replicas of the transmission. They also provide spatial diversity through the independent fading channels between distinct node pairs. As explained in [Hunter and Nosratinia, 2006] that, Cooperative Coded (CC) framework is very flexible and can be used with virtually any channel coding scenario. For example, the overall code may be a block or convolutional code, or a combination of both. The code bits for the two frames may be partitioned through puncturing, product codes or other forms of concatenation. As shown in Figure 5.6c, the wireless nodes make joint partnership to transmit their signal. The relay node selection is either made by the source node or the base station. The selection strategy should not be overly complex and then two partners should

use a cooperative strategy maximizing the throughput [Sendonaris et al., 2003].

(a) Amplify and Forward   (b) Decode and Forward   (c) Coded Cooperation
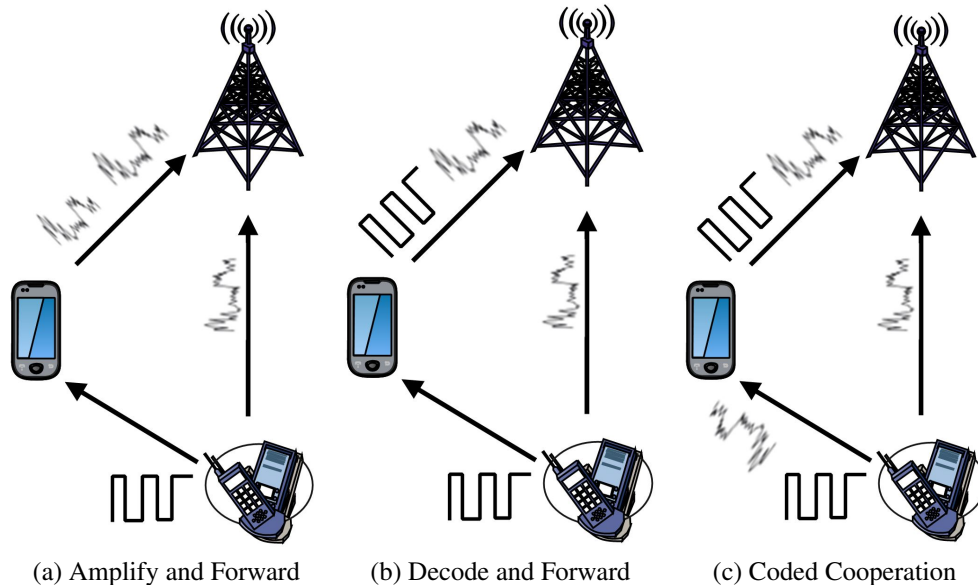
Figure 5.6: Delay minimization with network coding technique.

In the context of cooperative communications, several schemes focused on MAC layer which have been already proposed in the literature, such as [Liu et al., 2005] [Lu et al., 2007] [Alonso-Zarate et al., 2008] [Zhu and Kuo, 2008] [Guo and Carrasco, 2009]. The authors in [Antonopoulos et al., 2012] stated that the selected literature can be classified into two main categories as the following:

1. The cooperative Automatic Repeat ReQuest (ARQ) based protocols.

2. The protocols that transform one-hop transmissions to multi-hop transmissions by exploiting multi-rate capabilities of the wireless system.

These are discussed in the following sections.

5.3.4 Cooperative ARQ-based protocols

Forward Error Correction (FEC) and Automatic Repeat reQuest (ARQ) algorithms are two basic error control methods for data communications [Lin and Jr., 1984]. Compare with FEC algorithm, ARQ algorithm have received considerable attention for the data transmission due to their reliability and simplicity. Regarding the protocols falling in this category [Lu et al., 2007] [Alonso-Zarate et al., 2008], the retransmissions are initiated by the destination after an erroneous packet

reception. The helper nodes named intermediate nodes in a network are enabled to relay the original data packets to a designated destination node, as ARQ defines that using higher data rates or better channel conditions which is without error in term of Signal-to-Noise Ratio (SNR) value.

In the context of VANETs, the authors in [Kaul et al., 2008] have proposed a new MAC protocol named GeoMAC. This protocol exploits spatial diversity by allowing the communication nodes adjacent to the source node to opportunistically forward data packets. In Geo-MAC, the stations use a geographically-oriented backoff mechanism which uses the geographic distance to the destination as a heuristic to select the forwarder most likely to succeed. VC-MAC is another cooperative ARQ protocol proposed by [Zhang et al., 2008]. VC-MAC is designed specially for broadcasting in VANETs scenarios. Specifically, as the vehicles are moving very fast in vehicular network, the probability is high that after a certain period of time they will be outside the radio range of specific gateway that broadcasts data packets. However, other vehicles which are moving relatively at the same speed will remain in their proximity, thus being potential relays. Angelos Antonopoulos [Antonopoulos et al., 2012] proposed a new ARQ protocol named Network Coding-based Cooperative ARQ-MAC (NCCARQ-MAC) protocol. NCCARQ-MAC has been designed to coordinate the transmissions among a set of relays that support a bidirectional communication between two nodes in a vehicular environment. NCCARQ-MAC is designed to acehive the following two important objectives as follows:

1. The first goal of NCCARQ is to enable the mobile stations to request cooperation by the neighboring nodes upon an erroneous reception of data packets.

2. The second design goal of NCCARQ-MAC protocol is to allow the helper nodes to perform network coding techniques 5.3.2 to the packets to be transmitted before relaying them.

In NCCARQ-MAC, Firstly, a cooperation phase is initiated once a data packet is received erroneously by the destination node. Some factors phase erroneously by the destination node. There might be some factors that adversely effect on the correct data reception e.g. the long distance between the sender node and receiver node, the slow fading and shadowing inside dense populated areas e.g. urban area

where buildings are the cause etc. Several error detection mechanisms such as Cyclic Redundancy Code (CRC) can be applied in order to perform error control to the received messages. Secondly, therefore the destination station initiates the cooperation phase by broadcasting a Request For Cooperation (RFC) message after sensing the channel idle for Short Inter Frame Space (SIFS) period of time. This message has the from of a control packet and higher priority over regular data traffic, since data transmissions in 802.11 take place after a longer period of silence DCF Inter Frame Silence (DIFS) [Antonopoulos et al., 2012]. Furthermore, in the special but not rare case of bidirectional traffic, i.e. when the destination station has a data packet for the source station, the destination station has a data packet for the source station, the packet broadcasted piggybacked on the RFC message.

The network stations that receive the RFC data packet from other demanded node are potential candidates to become active relays for the communication process. Therefore, the relay set is formed upon the reception of the RFC and the participants stations get ready to forward their information. Since the partners have already stored the packets that destined both to the destination (so called cooperative packet) and to the source (so called piggyback packet), they create a new coded packet by combining the two exiting data packets, using the XOR method. Accordingly, the active relays will try to get access to the channel in order to persistently transmit the network coded.

5.3.5   Single hop to multihop transmission protocols

This type of protocols used an adaptive modulation concept as stated in [Morinaga et al., 1997]. The mobile stations in a multi-rate wireless network assign the modulation scheme and the transmission rate according to the detected Signal-to-Noise Ration (SNR) and the required transmission quality. These modulation scheme could be further mapped to a range of SNR in a given transmission power. To achieve high transmission efficiency in wireless systems, stations selects the highest available rate modulation scheme according to the detected SNR.

The classified example protocols are [Liu et al., 2005] [Guo and Carrasco, 2009] and [Zhu and Kuo, 2008], which transform single one-hop transmissions to multihop transmissions according to the channel conditions. Specifically, when the channel state between the relay node and destination node is better than the channel between the source

and destination. The stated authors proved that two-hop transmission is outperform than direct transmission. Another novel protocol called ADC-MAC [Zhu and Kuo, 2008] coordinates the scheduled transmissions with regard to the channel conditions among the source, the destination and the relay nodes in VANETs environment. In this protocol, a three-party hand shake scheme take place between the nodes in order to be decided which is the most efficient way for the data to be transmitted. Thus, a slow one-hop transmission can be transformed into a faster two-hop or more-hop transmission and the proposed scheme utilizes multiple channels for parallel transmissions for decreasing the transmission time and increasing the throughput significantly.

5.4   Problem Statement

The collision avoidance operation of IEEE 802.11 [IEE, 2016] standard is performed by variable to control users access times. The appropriate stations start to transmit their frames randomly to reduce the probability of collisions. However the collision may still occur if two or more stations involved have to reenter the competition cycle with an exponentially increasing backoff parameter value, and the increase of backoff parameter value after collisions is the mechanism provided by CSMA/CA to make the access control adaptive to channel conditions. This strategy avoids long access delays when the load is relatively light because it selects a small initial parameter value of contention window (CW) by assuming a low level of congestion in the system. However, it incurs a high collision probability and channel utilization is degraded in bursty arrival or congested scenarios. Furthermore, after a successful transmission, the size of CW is reset again to the minimum value without any memory of the current channel status. In addition, the performance of the CSMA/CA access scheme will be severely degraded not only in congested scenarios but also in a situation where bit error rate increases in the wireless channel. The fundamental problem arise here come from backoff algorithm. During the transmission in CSMA/CA, sender node successfully receive acknowledgment of each data frame immediately. This is accomplished by a receiver initiating the transmission of an acknowledgment frame after a small time interval, SIFS, immediately following the reception of the data frame. If the acknowledgment of the data is not received on time then the sender should automatically presume the data frame that was lost due to collision. Consequently, when a timer goes off, it exponentially increase backup parameter value and retransmits the data

frame less intensively. Unfortunately, during bad condition, such as high mobility, dense traffic, worse weather etc., the wireless links are too noisy and highly unreliable. Path loss, channel fading, channel noise and interference may cause significant bit errors. It means that an unacknowledged frame could result from not only collisions but also frame loss. Furthermore, In VANETs, the performance is often effected by many factor such as fading, interferences operating simultaneously, and the most important is the high velocity etc. The time-varying properties of wireless channels may lead to performance deterioration, like packet loss, packet damage etc. In such cases the retransmissions of packets are required. Also, due to a short setup time of the wireless links between the mobile nodes which influence on the data transmission, it is needed to design an appropriate way to adjust the contention window based on the vehicles velocity. In fact, the network coding technique has attracted great interest because it allows intermediate nodes in a communication network to not only forward but also combine their incoming independent information flows. The capability of combining independent data steam allows the information flows to be better tailored in a particular environment to meet the demands of specific traffic patterns. The fundamental question in this context, and the focus of this chapter, is to design and develop an efficient network coding algorithm that take into account cooperation among mobile nodes and multiple interfaces.

5.5   Cooperation and Network Coding MAC Protocol

The proposed protocol named Cooperation and Network Coding MAC (CNC-MAC) Protocol. When a mobile node receives an erroneous data packet, it requests for cooperation from its neighbor nodes by Request for cooperation (RFC) packet. Thus, each neighboring node is able to send its information along with the RFC packets to its neighbor nodes. Once the nodes received the RFC, they become an active relays. As the destination node can inquire assistance from relay nodes by sending RFC. The destination node moves fast and the probability of going out of the source's or the nearby relay nodes radio range is high. Therefore, the time left for repairing broken packets and hence the size of the data packets is inherently confined. When receiving an erroneous packet, the destination node broadcasts RFC to its neighbor relay nodes, including the received erroneous packet. When each potential relay node receives the RFC packet together with the corrupted data, NC and XOR are applied, triggering the creation a new coded packet, containing just the corrected part was erroneous in the packet received. The relay node tries to gain access the

channel and to broadcast the repair data. Minimizing the repair data ensures short data packets, thus minimizing the probability for the destination to still be in the radio range for reception. Our proposed protocol is formally provided in Aglorithm 3

Algorithm 3 CNC-MAC Protocol

Notation:

S, D : ID's of the source and destination nodes

N_i : Intermediate relay nodes R_i where $i = 1, 2, 3$

RFC : Request for cooperation

A : Original data packet

B : Received erroneous data packet

Ack : Acknowledgment

Upon request packet A from D

S broadcast A in Ni

  1: **if** $(n_i == D) \& S \in D$ **then**

  2:     Send packet $A \rightarrow D$

  3:     **break**

  4: **else**

  5:     **if** D goes out from the N_i list $\& D \neq N_i$ after time T **then**

  6:         **while** D received erroneous packet A **do**

  7:             D request for RFC along with packet B (i.e. $RFC + B$) to $R_2 \in N_i$

  8:             $R_2 \in N_i$ broadcast $RFC + B$

  9:             **while** $R_3 \in N_i$ is reachable to D **do**

10:                $R_3 \in N_i$ apply $A \oplus B$ and forward to D

11:                D sends Ack to $N_i \rightarrow S$

12:             **end while**

13:         **end while**

14:         Transmission completed

15:     **end if**

16: **end if**

The proposed CNC-MAC is explained with the help of an example as exemplarily demonstrates in Figure 5.7. Cooperation and Network Coding MAC (CNC-MAC) protocol works on bidirectional communication among a set of nodes. In this simple scenario a packet A is sent from source S to destination D. D receives A while detecting an error, for instance via Error Detecting Codes (EDC). D then labels the erroneous package as B, and broadcasts it together with a RFC. Then, B and the RFC are received by relay $R2$, which realizes that it will be out of $D's$ range soon. So $R2$ broadcasts B and the RFC which are eventually received by $R3$. This relay earlier received A from S and can now compute with NC the XOR operation $A \oplus B$, broadcasting the result afterward. The result is received by both S and D who confirm the correctness.
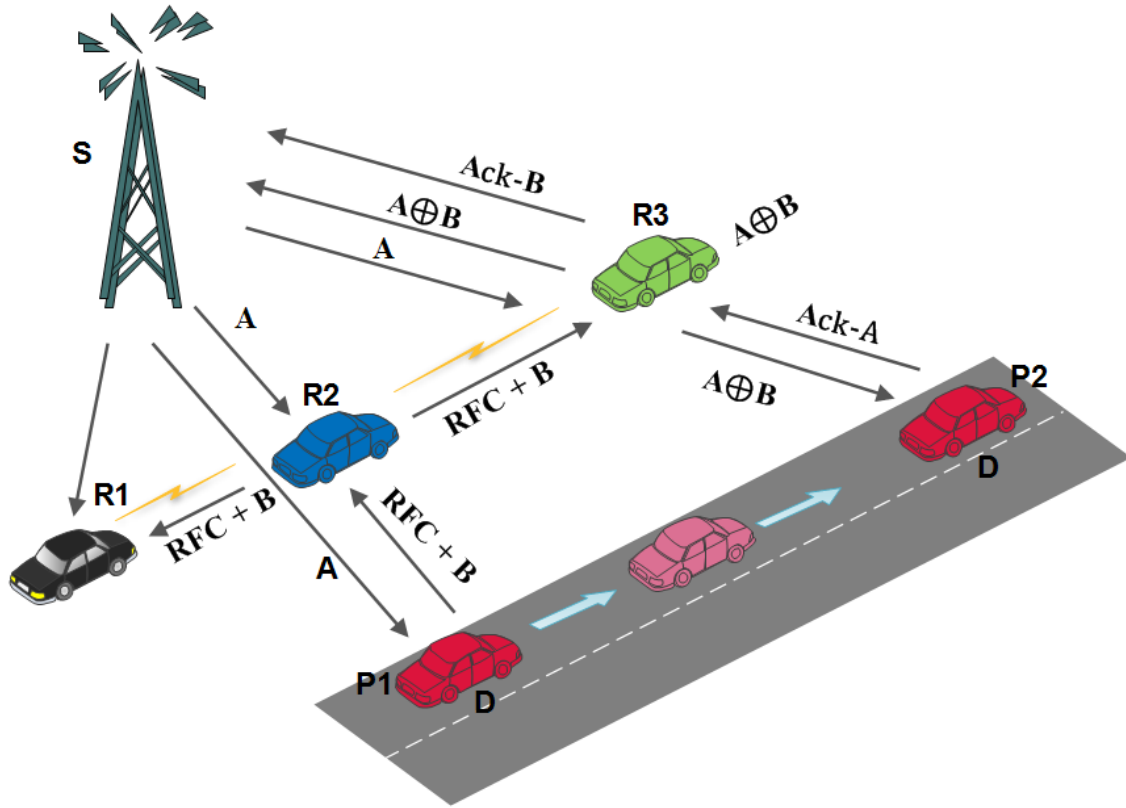
Figure 5.7: An operational example of the CNC-MAC protocol.

CNC-MAC employs the same frame structures and principles of the IEEE 802.11p standard [IEE, 2016]. The following steps are considered:

- All data types have equal priority.

- Communication is bidirectional and data packets confirmed via acknowledgment (ACK) packets.

- To simplify our model we consider error free channels between source and relay, relay and relay as well as relay and destination.

- The destination node being highly mobile implies that there is no contention phase among the relay nodes to get access to the channel.

- For the protocol to work, the destination node should be in communication range of its nearby relay nodes.

- Since NC is carried out only on two packets (A and B) at a time, computational cost is considered negligible.

5.5.1   Contention Window Adjustment

The authors in [Wang et al., 2008] present that a constant backoff window size does not guarantee the desired throughput in the vehicle to infrastructure

(V2I) environment. Also, simulation and analytical results indicate that IEEE 802.11p suffers from an undesired decrease in throughput and increase of delay in high node-density scenarios. When a node inquires access to the channel and the channel is busy, then it creates a Contention Window (CW). The contention window is minimal for cars traveling at average speed (10m/sec to 40m/sec in the featured simulation setup), while it increases the more cars deviate from that speed. It becomes maximal for very slow and very fast cars.

Vehicles are equipped with a Global Positioning System (GPS), determining state vector information. This includes node identifier (ID), speed vector, timestamp and node position. This allows to calculate the distance between the nodes. When the relay node receives an RFC, it also receives the state vector information and the erroneous data packet. Then it computes for how long both nodes are in each others range. For this it exploits the average velocity of itself and of the destination node, and the deviation ΔV of its velocity from the average velocity V_{avg} and for the destination node as well. The relay nodes adjust the values of the minimum and maximum contention window sizes $CWmin$ and $CWmax$ according to the amount of time that both are in each others range. The following equation shows this computation:

$$\Delta V1 = |V_{avg} - VR|$$
$$\Delta V2 = |V_{avg} - VD|$$
$$CW = \Delta V1 - \Delta V2$$
If $\Delta V1 = \Delta V2$ then $CW_{current}$ will set to $CWmin$
If $\Delta V1 > \Delta V2$ then $CW = CW_{current} - \Delta CW_{(t)}$
If $\Delta V1 < \Delta V2$ then $CW = CW_{current} - \Delta CW_{(t)}$
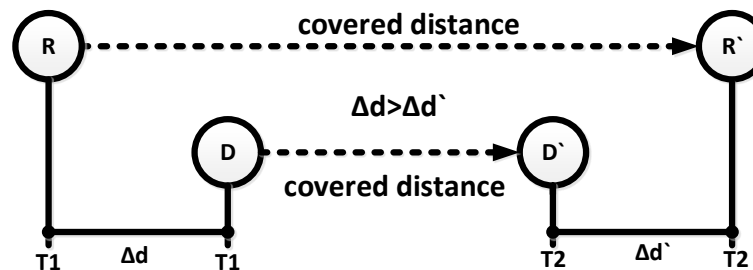
This scheme aims at optimizing the backoff mechanism in the MAC protocol by assigning a dynamic CW size according to node mobility parameters.
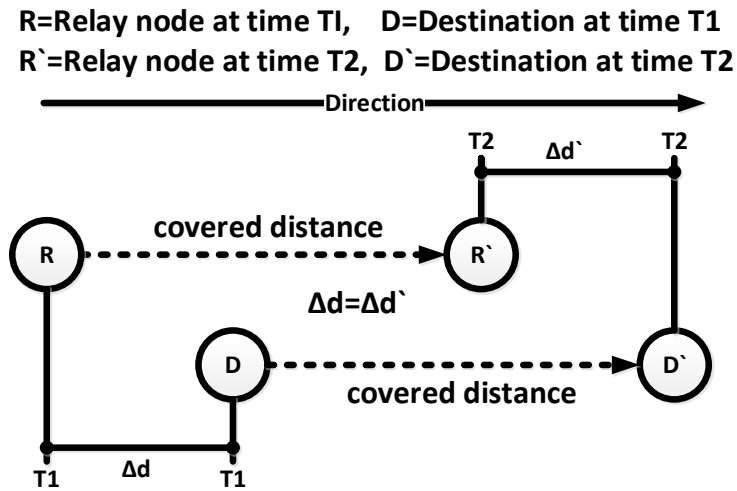
(a) Case-1
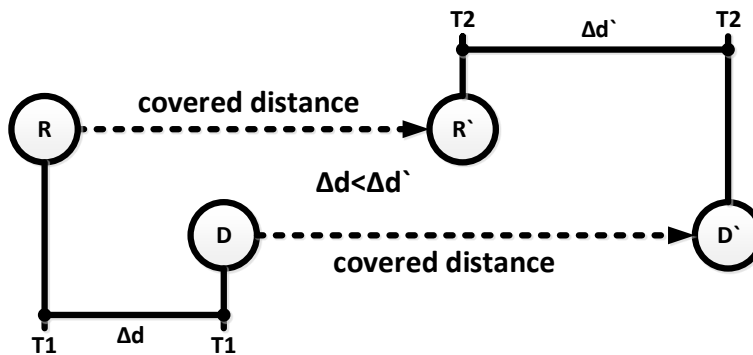
(b) Case-2

(c) Case-3

Figure 5.8: Three cases of Contention Window (CW) size adjustment based on velocity

Figure 5.8 illustrates three cases:

(a) In the first case relay node R and destination node D have same speed,

(b) Destination node D is faster than relay node R, and

(c) Relay node R is faster than destination node D.

The CW adjustment defines the resident time i.e. the amount of time the nodes can communicate. Figure 5.8a illustrates the case-1 where both nodes having the same speed. After certain period of time i.e. between $T1$ to $T2$, the covered distance is $\Delta d = \Delta d`$ hence, CW is initialized from $CWmin$.

The case-2 which is depicted in Figure 5.8b shows that the relay node R moving with normal speed that is less than the destination node D which is moving with high speed, then after certain period of time i.e. between $T1$ to $T2$, the difference of the distance covered is $\Delta d < \Delta d`$ and hence $CWmax$ is chosen.

Figure 5.8c shows the case-3 which is the adverse case. As shown, in this figure the relay node R is moving high speed while the destination node D is moving with less velocity. After certain period of time i.e. between $T1$ to $T2$, the difference of the distance covered is $\Delta d > \Delta d`$ and hence $CWmax$ is chosen.

The time point D is getting out of $R`$ range is labeled $T$, i.e. the time at which the difference between distances $D, D`$ and $R, R`$ is maximal admissible for communication. Due to the impact of speed and less setup time in the radio range, CW should be adjusted up to some value $CW_{current} - \Delta CW_{(t)}$ according to the lifetime within the active radio range of the relay node.

5.6 Performance Evaluation

This section presents the performance evaluation of the proposed CNC-MAC protocol by using a time-driven C++ simulator. The simulations consist of a source, destination and three relay nodes. Each node can transmit, receive and buffer data. The relay nodes can perform the operations of NC on the received data in their buffers. Due to the effect of relative speed the CW size is set to be dynamic. Relay and destination nodes travel at a speed of 10-40 m/sec in the same direction and have a radio range of 80m. Considering IEEE 802.11p physical and MAC layers, the size of each data packet is set to 1500 bytes, a MAC header of 34 bytes, plus ACK and RFC assembling to 14 bytes. The data rate is set to 3Mbit/sec and the MAC buffer is 14 frame. Three values $CW_{min} \in \{3, 7, 15\}$ are tested for minimal, and three values $CW_{max} \in \{63, 255, 1023\}$ for maximal contention window sizes. The proposed CNC-MAC protocol is compared with the Cooperative ARQ MAC (CARQ-MAC) protocol. CARQ-MAC is chosen to compare with the proposed scheme because of its simplicity and higher reliability, compared with others e.g. Forward Error Correction (FEC). In CARQ-MAC protocol the destination node sends a cooperation

request packet to the relay nodes once it receives an erroneous packet. The relay nodes establish a connection with the destination and forwards the packet to the source node. No NC operations are performed in CARQ-MAC by the relay nodes on the received data from the source or destination nodes.
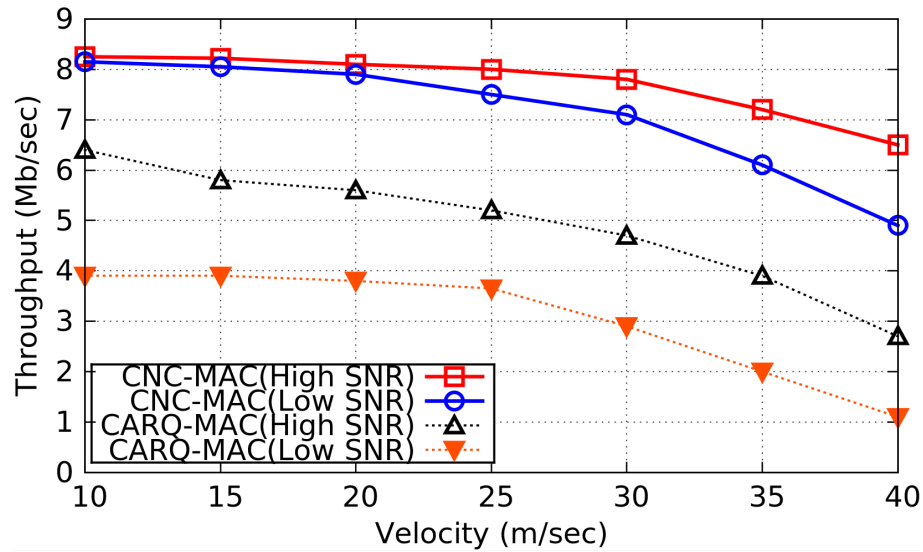

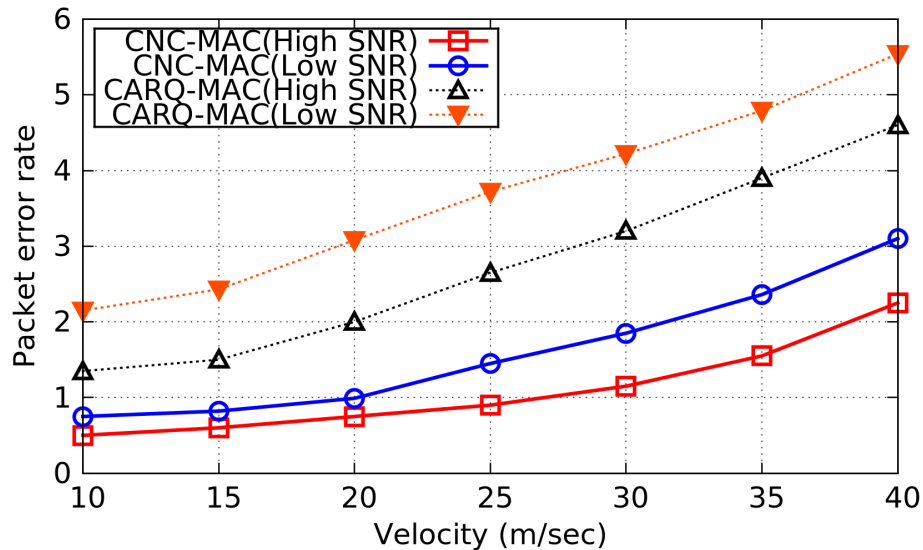Figure 5.9: Throughput vs. Velocity

Figure 5.10: Packet error rate vs. Velocity

The Figure 5.9 shows that the throughput can be enhanced by up to 80%-90% comparing the CNC-MAC with the CARQ-MAC protocol. For both high and low SNR the CNC MAC outperforms the CARQ-MAC by means of throughput. This advantage is gained by NC reducing the number of transmissions significantly. This is mainly because the network topology does not change significantly when the nodes do not move fast. But, when the node speed varies from 10-40 m/sec the performance of average network
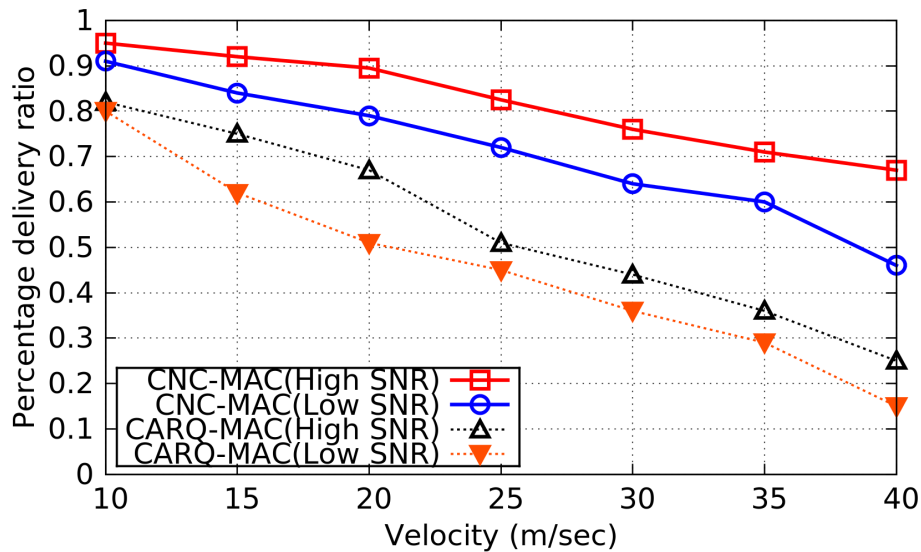
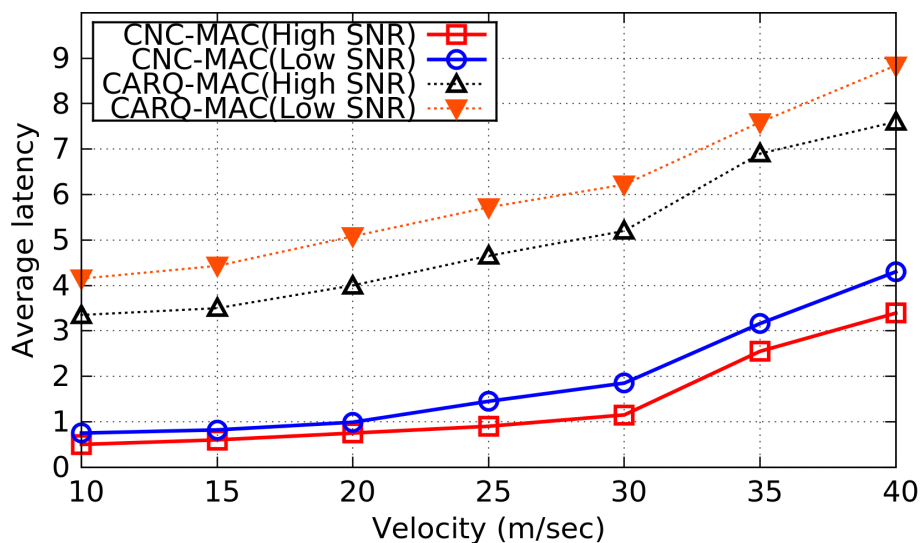Figure 5.11: Data delivery ratio as a function of velocity

Figure 5.12: Average latency as a function of velocity

connectivity of CARQ-MAC is found to decrease dramatically due to the topology being highly dynamic. High dynamics result in low throughput. The CNC-MAC protocol utilizes the cooperation phase and broadcasts the received packet from the destination to the nearby relays which further transmit these packets to the neighbor relays thus, the high speed destination node remains in the coverage area of at-least one relay. CNC-MAC shows a better performance in terms of throughput with variable maximal velocity.

Figure 5.10 compares the packet error-rates of both CNC-MAC and CARQ-MAC protocols. In both low and high SNR scenarios CNC-MAC outperforms CARQ-MAC. In case of high mobility of D, CARQ-MAC drops more packets due to an increased number of transitions. Thus the number of packet-errors increases. For instance, when destination node D sends the

data packet B+RFC to the relay node R2, it moves faster towards R3. R2 can successfully relay the packet to S, but the acknowledgment from S to D via R2 gets lost due to mobility and thus D has to retransmit the lost packets (Data and ACKs). On the other hand, in CNC-MAC the message from D is broadcast to R1 and R3 via R2. Then, D receives the packet via R2 at position P2.

In Figure 5.11, it is observe that increasing mobility in CARQ-MAC decreases the delivery ratio dramatically for both high and low SNR. This is because it adjusts the contention window in response to mobility.

Figure 5.12 shows that, as mobility increases, chances of contention, frame errors and retransmission increase. In the event of mobility, the latency values increase for CNC-MAC, but without large variations. The latency increase in the comparative protocol is caused by the increasing number of retransmissions due to frame errors.

5.7 Chapter Summary

In this chapter, Network Coding (NC) were discussed with there different features along with the selected literature. A new novel MAC protocol named Cooperative and Network Coding MAC (CNC-MAC) protocol is presented covering the transmission failure issues utilizing NC technique. Furthermore, Contention Window (CW) adjustment scheme is proposed according to the nodes velocity. The proposed CNC-MAC protocol is evaluated by using time-driven C++ simulator against with its counterpart conventional Cooperative Automatic Repeat ReQuest MAC (CARQ-MAC) protocol and checked that how the throughput, packet error rate, packet delivery ratio and latency are effected against velocity. CNC-MAC protocol exploits the advantages of cooperative communication and network coding techniques to outperform the CARQ-MAC as selected. CNC-MAC allows to enhance throughput up to 80%-90% by minimizing the number of transmissions. Furthermore, CNC-MAC MAC performs better under high mobility and significantly reduces the number of packet loss.

6. A Hybrid MAC Scheme for Emergency System in Urban VANETs Environment

6.1   Introduction

Driven by road safety requirements and intelligent traffic control, Vehicular Ad-hoc Networks (VANETs) have been attracting significant interest in both academia and industry. VANETs are distributed, self-organizing communication networks comprising moving vehicles which contain both inter-vehicular (V2V) and vehicle-to-infrastructure (V2I) communication. The communication requirements for traffic safety slightly differ from the wireless communication requirements for other applications. E.g. one of the requirement is the reliable and timely communication among the nodes of the distributed system.

Several wireless technologies can be applied to the transportation systems for their safety and efficiency. VANETs in particular focus on V2V and V2I communication [Toor et al., 2008]. This enable services to increase safety

via critical applications (e.g. collision warning and traffic coordination) as well as non-critical applications (e.g. shared internet access and multimedia data transfer between vehicles).

An IEEE working group investigates a new PHY/MAC amendment of the 802.11 standard designed specially for VANETs system. Requirements for IEEE 802.11p are mostly coming from vehicular active safety concepts and applications i.e. inter-vehicular communications or vehicle-to-infrastructure, where reliability and low latency are extremely important goal. V2I initiative, first time in the United States recommended that, the critical information (accident, hazard warning) should be transmitted through VANET within half a second to all equipped vehicles in a 500 meter range. In terms of Medium Access Control (MAC) operations, IEEE 802.11p utilizes Carrier Sense Multiple Access (CSMA) as the basic medium access scheme for link sharing, and should probably use one control channel to set up transmissions, which then should be done over some transmission channels.

The MAC protocol for VANETs is crucial to provide for an efficient and reliable medium access. The challenge is to design the protocol to be able to cope with rapid topology changes, high node mobility [Menouar et al., 2006] and different QoS requirements. Safety applications require high reliability and a bounded delay, while non-critical applications are rather throughput sensitive [Bi et al., 2008]. V2V communications use the Dedicated Short-Range Communication (DSRC) 5.9 GHz frequency band used in United States, which is a limited spectrum source. In 1999, the U.S. Federal Communications Commission (FCC) allocated seven 10-MHz channels in the 5.9 GHz band, comprising one Control Channel (CCH) and six Service Channel (SCHs) for safety and non-safety applications respectively. In fact, DSRC is an American nickname for IEEE 802.11p, whereas in Europe the DSRC refers to master-slave tolling system standardized by European Committee for Standardization (CEN). Similarly, IEEE 802.11p and its associated European frequency band is nicknamed ETSI ITS G5 in Europe. This encouraged researchers to design a multi-channel[1] structure for the MAC protocol considering a system that operates in the United States, as shown in Fig. 6.1. Messages on the SCH are categorized into routine and real-time messages. The routine messages are beacon messages while the real-time messages are termed emergency messages in this literature. By partitioning different services and terminals on different channels, a multi-channel MAC protocol can increase communication throughput

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[1]A channel is defined as a frequency interval over which nodes communicate. The terms "channel" and "frequency" are synonymous here.

and decrease network latency [Mo et al., 2008]. The protocol specified under the IEEE 802.11p standard - which is commonly applied for VANET applications [Jiang and Delgrossi, 2008][IEE,] - divides time into 100ms intervals, referred to as sync intervals. Furthermore, each interval is then divided into two halves, one Control Channel Interval (CCHI) and one Service Channel Interval (SCHI) of 50ms each.
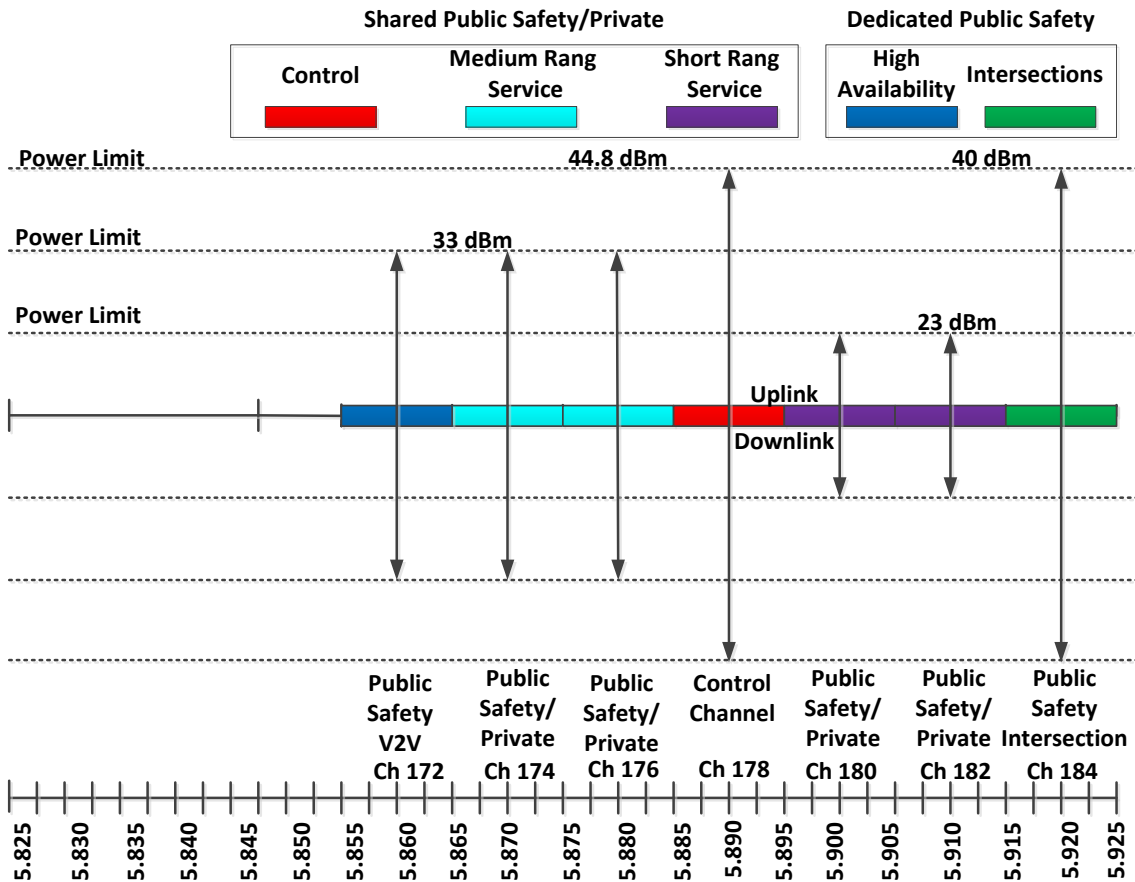

Figure 6.1: Federal Communications Commission (FCC) Spectrum

This chapter presents Hybrid MAC (HyMAC) [Khan et al., 2017], a scheme tailored for broadcasting emergency messages in urban VANETs. The challenge of urban VANET is to cope with the frequent obstructions which are blocking the radio transmissions. HyMAC is based on a real-time channel access mechanism, it exploits the Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) techniques, and also, it exploits the real-time channel switching (considering CSMA and TDMA for the channel switching simultaneously). The summary of the contributions for this chapter are:

1. HyMAC is designed in such a way, that CSMA and TDMA can switch dynamically in emergency situations.

2. It takes into account the density and the dynamics of the vehicles, allowing for optimizing the utilization of the CCH leading to increased throughput and reduced latency

3. An explanation, how equally prioritized emergency messages are scheduled a fully distributed way

4. A comparison of HyMAC with the conventional standard IEEE 802.11p and VeMAC protocols in terms of transmission delay, throughput as well as collision rate.

A node selects the MAC protocol mode according to the situation, depending on the specific traffic pattern in its environment. This can lead to situations in which a node switches the mode of the complete network for all other nodes. It requires that, the particular node is able to communicate about that mode switch, utilizing multiple different MAC protocols (CSMA/TDMA). The proposition of HyMAC scheme has the following advantages:

- HyMAC utilizes local state vector information to improve communication (reduce delay, increase throughput).

- It reduces flooding on the CCH by limiting the broadcast to fixed regions.

- A region is maintained by a Region Head (RH). The RH is a dynamically determined node (e.g. via leader election [Fischer and Jiang, 2006] [Nesterenko and Tixeuil, 2009]).

CSMA and TDMA are contention and schedule based protocols and common MAC access mechanisms. This chapter proposes a decentralized TDMA MAC for VANET to replace CSMA for safety applications. However, exploiting TDMA comes at a price, such as i) the overhead of the slot allocation and ii) low channel utilization.

The remainder of this chapter is organized as follows: Section 6.2 motivates the study. The related work with different techniques, definitions and selected literature is presented in 6.3. Section 6.4.1 presents the system model and Section 6.4 describes the proposed MAC scheme along with table formation and data entry, and the method how to change the mode of a system from normal to emergency according to the situation. Evaluation results are shown in Section 6.5 and the chapter concludes with a summary (Section 6.6).

6.2 Motivation

In VANETs safety applications, vehicles have to be constantly aware of the events in their surrounding environment to prevent dangerous situations before they occur. A common challenge in wireless communication network is collision, resulting from two or more nodes sending data at the same time over a common transmission medium or channel. Medium Access Control (MAC) protocols have been developed to assist each node to decide when and how to access the channel. This problem is called channel allocation technique or is also known as channel access problem [Ye and Heidemann, 2003]. CSMA and TDMA are the two basic MAC protocols. Although, there have been significant recent innovations at different protocol layers which maximize the network throughput at MAC layer in a multi task network, which is still a key challenging point. Furthermore, the vehicles in the network have to periodically exchange their status every time and emergency messages during the critical situation. Without reliable and efficient MAC protocol such high rate of messages may result in a large number of collisions. This kind of problem is very common in city area where the traffic density is high. By keeping these challenges in front, an efficient and reliable MAC scheme should avoid the collision probability between nodes and efficiently utilize the channels (CCH and SCHs) during the emergency situation.

6.3 Related Work

Safety applications exploiting VANETs require a preferably deterministic Medium Access Control (MAC) protocol. Although tremendous efforts in this domain accomplished a lot, but the goal has not been reached yet. Such as, Vehicular-to-Vehicular (V2V) technology can minimize many potential traffic hazards and prevents many accidents by exchanging crucial information between vehicles which is obtained by sensing a vehicle's situation, driver's health condition, road condition, surrounding vehicles, and so on. The challenge is to provide a deterministic channel access under high load conditions. Existing MAC mechanisms fail to fulfill this requirements for safety applications in VANETs.

Previous studies focused on improving the channel utilization and its management. For instance, [Zhang et al., 2014a], [Zhang et al., 2014b] and [Bejaoui, 2014] increase channel throughput by adopting an adaptive Control Channel Interval (CCHI) depending on network density and a Time Division Multiple Access (TDMA) mechanism. CSMA and self-Organizing TDMA

MAC (CS-TDMA) has been proposed by [Zhang et al., 2014a] combining CSMA and TDMA to improve the broadcast performance in VANETs. CS-TDMA differs from all the other multi-channel protocols, such that, the ratio between the CCH and SCH intervals is dynamically adjusted according to traffic density. When the density of vehicles is low, the CCH duration is maximized to guarantee a bounded transmission delay for real-time safety applications. CS-TDMA achieves a significant improvement in DSRC channels utilization, but the performance evaluation of the CS-TDMA protocol has been limited only to a medium density of vehicles. Moreover, there is still a lot of research need to done on access collision and merging collision problems. Time Division Multiplexing Channel Coordination (TDMCC) [Zhang et al., 2014b] can assign synchronization interval and CCH priority queues dynamically according to estimated real-time VANET conditions. This scheme introduces the methods of synchronization interval partition and time-slot assignment during SCH interval. [Bejaoui, 2014] proposed a novel vehicle density-based call admission control scheme for vehicular networks, that dynamically adapts vehicles transmission powers and provides desired throughput guarantees to user performing communication within a real world like vehicular-to-roadside IEEE 802.11p communication networks. However, in this study, still the channel is not fully utilized because SCHs are not utilized during the CCHI.

Since the communication requirements of VANET safety applications are complex and demand high throughput, reliability, and bounded time delay. And, designing a MAC protocol addressing high throughput, reliability, and bounded time delay is a challenging task particularly in high-density networks. It is shown from previous studies, that using TDMA or Self-organized TDMA (STDMA) [Bilstrup et al., 2009] is fair and has predictable delay. However, it needs strict synchronization and complete pre-mapping of geographical locations to TDMA slots. On the other hand, using CSMA is less complex, as it supports variable packet sizes, and requires no strict synchronization, but it has problems in unbounded time delay and consecutive packet drops. Therefore, clustering is used to limit channel contention, and to provide fair channel access within the cluster, and to increase the network capacity by the spatial reuse of network resources, and to control effectively the network topology. The main challenge in clustering is the overhead that is introduced to elect the cluster head (CH) and to maintain the membership in a highly dynamic and fast changing topology. Optimization of the communication range and the cluster size, is also difficult, particularly in a highly dynamic environment such as VANETs. For channel

utilization improvement, [Hafeez et al., 2013] provides a Distributed Multi-channel and Mobility Aware Cluster-based MAC protocol (DMMAC). It integrates Orthogonal Frequency-Division Multiple Access (OFDMA) with the contention-based Distributed Coordination Function (DCF) algorithm in IEEE 802.11p. CHs are elected based on their stability on the road and with minimal overhead since clustering information is embedded in vehicle's periodic status messages. The proposed MAC protocol is adaptable to drivers behavior and has a learning mechanism to predict the future speeds and positions of all cluster members using the Fuzzy-logic Inference System (FIS). In [Tsogoo and Yoo, 2015], an efficient multi-channel mechanism called Multi-Schedule based Channel Switching (MSCS) is proposed. MSCS is a novel multi-channel MAC mechanism, it adopts multiple schedules to switch between the CCH and SCHs. In this scheme four separate periods of time are defined to access the CCH and the switch with SCHs. Therefore, not all nodes try to access the CCH at the same time, as in legacy IEEE 802.11p (WAVE).

ADHOC MAC [Borgonovo et al., 2004] uses the Reliable Reservation ALOHA (RR-ALOHA) protocol, a distributed reservation protocol that creates a reliable single-hop broadcast channel, the Basic Channel (BCH). Each BCH carries signaling information to solve both the hidden and exposed terminal problems, and to provide an efficient implementation of a network broadcast service. The basic idea is to have each terminal periodically transmitting the Frame Information (FI), i.e. the status of slots in the previous period (frame). Whenever new terminals want to get access to the network, they use this information. ADHOC MAC works independently from the physical layer, and its main disadvantage is that the medium is not used efficiently, and the number of vehicles that can communicate in a given region is not greater than the number of the time slots in the frame time. ADHOC MAC also require (tight) time synchronization, a feature not straight-forward to achieve in an Inter Vehicular Communication (IVC) system.

Another approach to control the medium access is the Vehicular Cooperative Media Access Control MAC (VC-MAC) [Zhang et al., 2008], which uses the concept of cooperative communication tailored for vehicular networks. This protocol takes advantage of the broadcast in order to maximize the system throughput. The broadcast is made by the access point based on the premise that under the information-downloading scenario, all vehicles are interested in the same information. During the transmission, due to the unreliability of the wireless channel, a group of vehicles may not receive the

right information. The vehicles that received the information will be then selected to relay the information to their neighbors. Therefore, to reduce the probability of having collisions and interference, the protocol uses only a part of the vehicles to create a group of good relays. As we can see, the protocols apply techniques to choose the relays based on the principle of maximizing the spatial re-usability of the whole network.

Considering the different types of control channels, such as [Shao et al., 2014] presents a MP-MAC protocol, which uses a technique to define different priorities to transmit a packet starting with safety packets and then control packets. It uses a multi-priority Markov process to optimize the use of the channel according to the network traffic. Besides, it implements a p-persistent MAC scheme to reduce the probability of collisions during the transmission.

VeMAC [Omar et al., 2013] is contention-free multi-channel TDMA MAC protocol which reserves disjoint sets of time slots in the CCH for vehicles moving in opposite directions and for Road Side Units (RSUs). In VeMAC each node has two transceivers. The first is tuned to the CCH and the second to a service channel. The assignment of time slots on the service providers in a centralized way. However, the size of each VeMAC packet transmitted by a vehicle on the CCH is relatively large. It contains the Vehicle ID, the current position, the set of one-hop neighbors and the time slot assigned to each node within one-hop distance. This increases the overhead of the VeMAC protocol on the CCH. In addition, its random slot assignment technique is inefficient due to the appearance of free slots.

6.4   The Proposed Hybrid Scheme

This preceding subsection introduces the system model for the proposed HyMAC scheme, and the table formation, and data entry on the road between the vehicles. Moreover, the approach of channel model switching and mode switching criteria is followed. The message delay during channel switching is also calculated as the section end.

6.4.1   System Model

Consider the scenario that two sets of vehicles move in opposite directions on a two-way road (right traffic) that is equipped with Road Side Units (RSUs). RSUs are considered as normal nodes, like parking vehicles, and the direction is defined as the same with the nearest vehicle on the road. A vehicle moves from left to right or in the opposite direction as shown in

Figure 6.2. This generalizes westbound and eastbound traffic as well as northbound and southbound traffic (while excluding crossings for simplicity here). The access time is partitioned into frames. Each frame is partitioned into two slots, one for left-bound and one for right-bound traffic. Each vehicle is considered to be equipped with a GPS receiver to precisely[2] determine location and direction. The GPS receiver also provides time synchronization via a 1 pulse per second (PPS) signal. This marks the time reference among all nodes and synchronizes the channel slots.
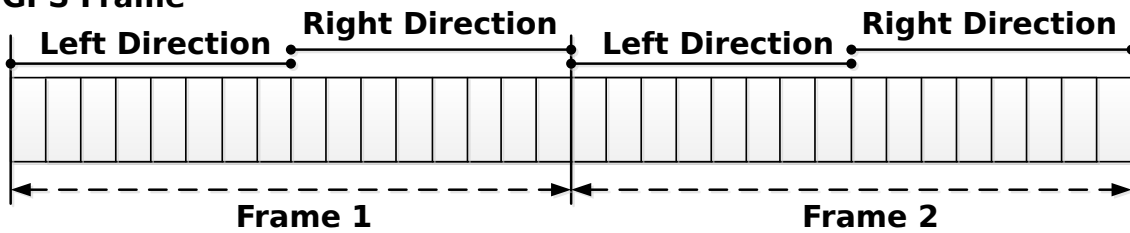
Figure 6.2: Right and Left Directions of Vehicle Movement
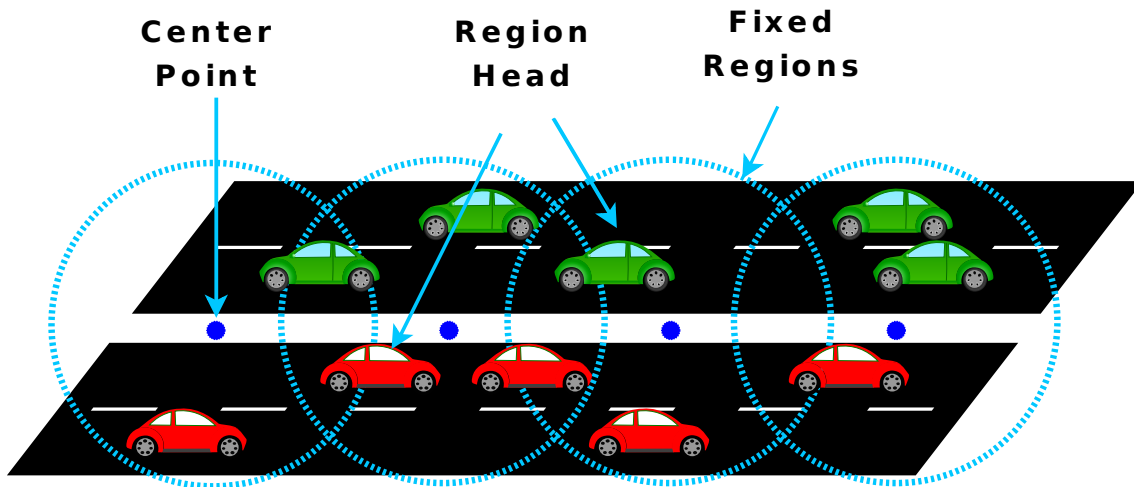
Figure 6.3: Road Network Structure

6.4.2 Table Formation and Data Entry

RSUs along the road delimit the regions. Cars within a region form a cluster of nodes that belong together by their proximity to RSU. Every node within a cluster knows about the receiving status of their neighbors. This ensures availability when distributing emergency messages and allows to avoid redundancy (i.e. rebroadcasting), thus reducing the channel load. Clustering is the process that divides all the vehicles in a network into organized groups

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[2]The accuracy of GPS in the civil sector is insufficient in this scenario. Yet, for simplicity, we consider GPS to allow for a sufficiently precise localization service if amended by secondary data provided by the RSUs and by interpolation with data provided by other cars.

called clusters. Several algorithms such as [Peng et al., 2008], [Christine et al., 2009] and [Mohamed et al., 2015] have been proposed for cluster formation that take into account the specific characteristics of VANETs. We proposed a mechanism based on the following statements. Table formation initializes by first forming the clusters. When the communication start, every node begins as a normal independent member of the networks, start timer and broadcast a HELLO message [Aquino-Santos and Block, 2006].

When a member receives a HELLO message from node i, it registers itself with the region head (RH) and responds with a reply HELLO message that notify its presence to its one-hop neighbors N_i. The HELLO message contains i) the vehicle ID, ii) the freshness, iii) the position, iv) the velocity and v) the direction of the vehicle (i.e. the responding vehicle respectively).

The most stable RH can be determined by minimum average euclidean distance to its neighbor, and the youngest member in region as it is most probables to stay the longest near to the region center point i.e. maximum average time stay with other neighbor nodes in the same radio region. The modified function from [Mohamed et al., 2015] is stated below in equation 6.1.

$$C_i = a\frac{\left(\sum_{j \in N_i} Dist|d_i,d_j|\right)}{(n_i \times t)} + b\frac{\left(\sum_{j \in N_i} V_t|v_i,v_j|\right)}{(n_i \times t)} - c(n_i \times t) \qquad (6.1)$$

where;

n_i: Number of neighbor nodes of node i,
$Dist|d_i, d_j|$: Euclidean distance between i and j where $i \neq j$,
$V_t|v_i, v_j|$: Velocity difference between i and j based on time,
N_i: The set of neighbors within node i radio range,
a, b, c: The weight coefficients, where $a + b + c = 1$.

The vehicle which has the minimum value of C_i is elected as the RH. This way, the emergency messages are delivered quickly to the destination after checking the neighbor table. Moreover, it is not necessary for the RH to flood the information within its own region.

6.4.3   Channel Mode Switching

This subsection explains the proposed hybrid MAC scheme.

Approach and Outline

The objective is to switch between CCH and SCHs without causing extra delay or additional network load. The proposed scheme treats CCH and SCHs as CSMA and TDMA respectively. For this, CCH is utilized as far as possible. Emergency messages are transmitted solely on CCH. Spare load on the CCH can be utilized by service messages. Nevertheless, emergency messages are always prioritized and emergency messages cannot be preempted (not even by other emergency messages). However, service messages can be preempted (regardless if on SCH or CCH).

The sending node estimates the duration for a successful transmission in terms of request - clear to send (RTS/CTS, [201, 2010]) - regarding all relevant data. Contention based protocols commonly have less delay and better throughput at low traffic loads. This is generally the case for wireless sensor networks. However, in VANETs, when the network load is high, there is a higher bandwidth overhead due to collisions and back-offs being more frequent. On the other hand, schedule-based communication has the inherent advantage of a collision-free medium access.

Consider the CCH is busy with other emergency messages and there emerges a new emergency message with a close deadline which has to be transmitted. After a certain number of attempts it switches the network mode to emergency to utilize the service channels. Switching the network mode stops all services like entertainment applications and allows emergency messages to be transmitted before their deadline. The SCHs remain reserved for emergency messages until each of them is determined to be successfully having been broadcast. In [Peng and Cheng, 2007] the author considers multiple priority levels for emergency messages. In contrast, our approach distinguishes only emergency from all other messages.

Mode Switching Criteria

The IEEE 802.11 standard specifies how all nodes access the shared medium employing CSMA. Figure 6.4 shows how a channel is accessed during normal operation (i.e. not during emergency). HyMAC employs a scheduler based on discrete time points. The channel access is controlled by TDMA, meaning channel access is granted a certain number of time intervals, also referred to as *slots*. Each time-slot allows for transmission of one or more packets. Proper channel switching ensures collision-free communication with multiple parallel[3] transmissions running simultaneously.

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[3]Concurrent from parallel by being unsychnronized has been distinguished. With discrete time slots allocated, communication in our case is synchronized and thus parallel.

Figure 6.5 shows the structure for the emergency mode. The time domain is discretised as before via short pulse detection. In the dynamic segment, the duration of communication slots may vary in order to accommodate frames of varying length. The frame ID enumerates the slots. In case the communication is unsuccessful after detecting short pulses [Peng and Cheng, 2007] on the CCH, the network mode switches to TDMA after arbitrating the remaining time in which the message should reach the destination. Pulses are basically single-tone waves with pauses in the control channel. As described above, the emergency messages are small compared to other messages. Inspired from the Flexray [Grenier et al., 2008], we also use the same segment slots. Hence, the required number of slots can be lower than the static segment slots. In the static segment, the numbered slots are fixed and are of equal length as shown in Figure 6.5.
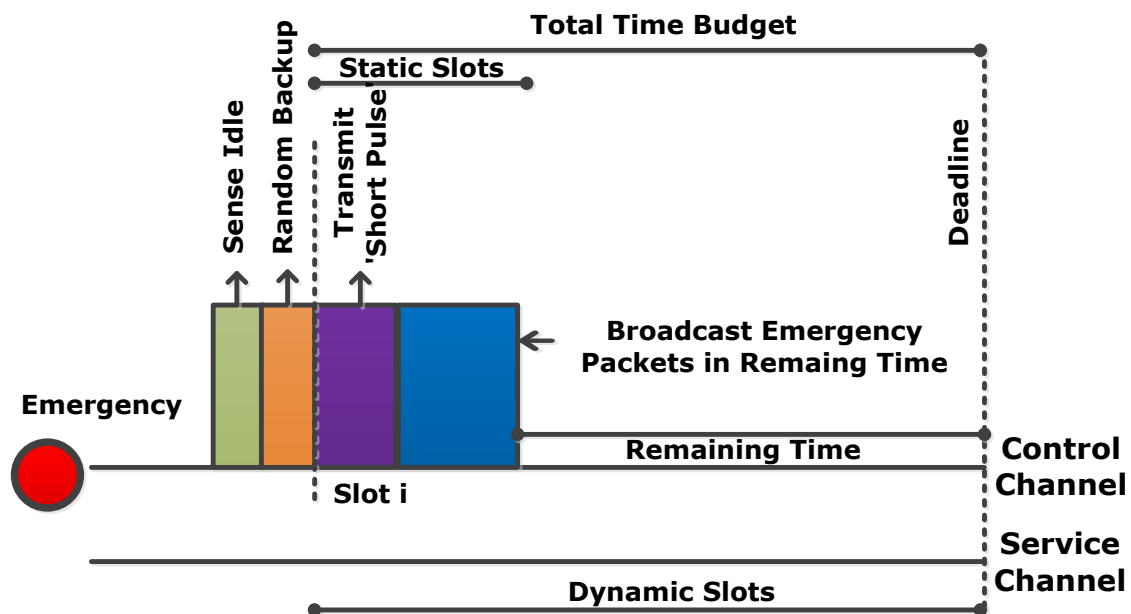
Figure 6.4: Multichannel Structure in Normal Situation

In the dynamic segment on the other hand, the length is specified via mini-slots. During the dynamic segment, in case no message is to be sent during a certain slot, then that slot will have a very small length, otherwise the dynamic segment will have a length equal with the number of mini-slots required for transmitting the whole emergency message by the transmitter. Shortening static slots to accommodate for short emergency messages helps in meeting deadlines. During any slot in a dynamic segment, only one node is allowed to send the message with the frame identifier. This scheme is provided in algorithm 4.
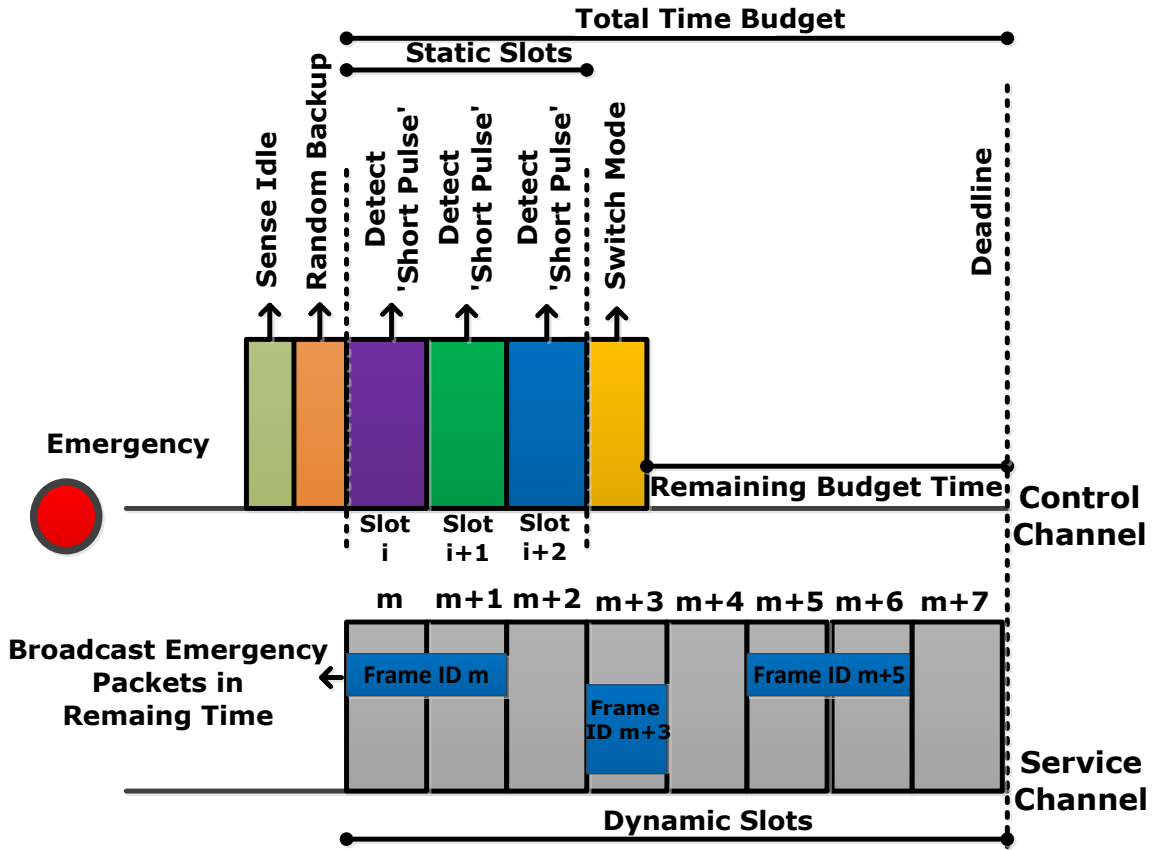
Figure 6.5: Multichannel Structure in Emergency Situation

Message Allocation after Channel Switching

An intelligent heuristic analysis allows for allocating the packets in the TDMA dynamic slots by determining if the system is schedule. The analysis is based on an approach by Pop et al. [Pop et al., 2000]. The following equation 6.2 describes the delay of message m in a queue q analysis:

$$\Im_m(q) = \left\lceil \frac{(q+1)P_m + I_m(w(q))}{S_p} \right\rceil \tag{6.2}$$

Here, P_m is the number of packets of a message m, S_p is the size of the slot (i.e. m is the number of packets and q is the delay). I_m is the interference when the channel is switched from CSMA to TDMA and $w(q)$ is the access delay. Messages are dynamically allocated to the frames as they are produced. Thus, when the channel switches, the number of packets is decided to be placed in the data field of the dynamic segment. However,

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Algorithm 4 Channel mode switching

Notation:

CCH : Control channel

SCH : Service Channel

M_P : Emergency packet

N_E : Emergency node

T_T : Total budget time

T_R : Remaining time

SP : Short pulse

S_i : Number of slots; where $i = 1, 2, 3, ...n$

$T_{(dl)}$: Deadline

Normal situation:

  1: **if** N_E receive M_P **then**

  2:    CCH is sensed idle $\rightarrow YES$

  3:    N_E take random backup & transmit SP

  4:    **while** $T_{(dl)} == T_T$ & $T_R \leq T_T$ **do**

  5:        **if** Another SP is not detected **then**

  6:            Broadcast M_P on CCH

  7:        **end if**

  8:

  9:    **end while**

10: **Emergency situation:**

11: **else**

12:    **if** N_E receive M_P **then**

13:        CCH is sensed idle $\rightarrow YES$

14:        N_E take random backup & transmit SP

15:    **end if**

16:    **if** Another SP is detected in CCH **then**

17:        **while** $T_{(dl)} == T_T$ **do**

18:            Start iteration to detect SP on S_i

19:            **if** $T_R \leq T_T$ **then**

20:                Stop the transmission on SCH

21:                Broadcast M_P on CCH

22:            **end if**

23:        **end while**

24:    **end if**

25: **end if**

---

this scheme is for the emergency messages so there is no restriction on the slot size.

A slot is constructed according to the messages size. Consider the simple example in Figure 6.6, where the messages m_1 and m_2 have different sizes, 6 bytes and 2 bytes. According to the scheme, the slots should be of dynamic size fitting messages m_1 and m_2. As they are emergency messages, there is no need to divide them to be the same size. In this example, with one
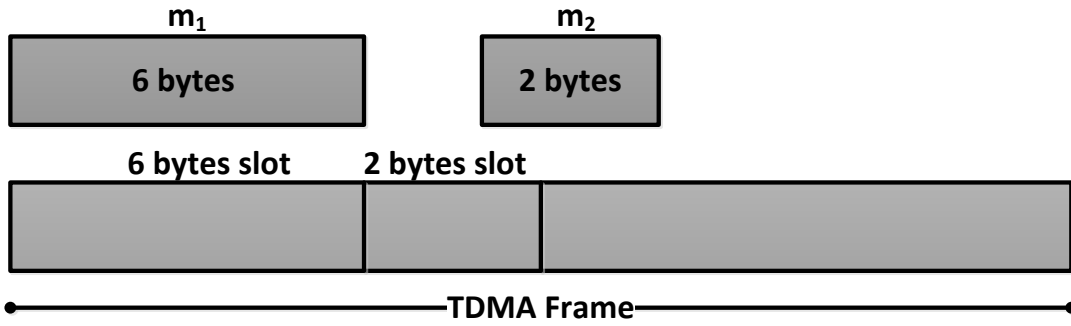
Figure 6.6: Message Allocation

sender and one receiver, the solution is simple. However, this is not the case in general but only during emergency modes.

Message Delay During Channel Switching

Emergency messages have real-time constraints. They adhere to deadlines $T_{(dl)}$ and must be delivered correctly to the recipients in a timely fashion. The delay in the MAC protocol $MAC_{(delay)} < T_{(dl)}$ addresses the constraints as shown in Algorithm 5. The service rate (μ) and the data rate (λ) are measured locally and disseminated within the region based on the present frame duration.

Algorithm 5 message delay in the mac protocol

1: **if** $T_{(dl)} \geq \mu_{csma}$ **then**
2:     run csma mac //@ *network normal situation*
3: **else**
4:     **if** $T_{(dl)} < \mu_{csma}$ and $\lambda_{csma} \leq \lambda_{tdma}$ **then**
5:         switch to tdma mac //@ *when the deadline is close during emergency*
6:     **else** Process fail **return**
7:     **end if**
8: **end if**

To calculate the delay during the channel switching time S_t, the transmission time T of the channel is defined as:

$$T = \{nL_m : nL_m \leq S_t\}, \tag{6.3}$$

Parameter	Value
Road Segment Length	1 km
Velocity	$[20, 50]$ km/h
Emergency Message Packet Size	512 bits
Normal Message Packet Size	512 bits
Beacon Packet Size	256 bits
Channel Capacity	6 Mbps
Wireless Data Rate	2 Mbps
Packet Duration	2 ms
Frame Size of CSMA	10 slots
Slot Size	20 μs
Radio Transmission Range	200 m

Table 6.1: Parameters used for simulations.

where L_m is the message length. The total number of attempts to access the channel to transmission are defined as:

$$N_{attempt} = \left\{ n : \sum_{i=1}^{n} S_t \geq L \right\}, \qquad (6.4)$$

Finally the total message delay T_{delay} of the message of size L is defined as:

$$T_{delay} = \sum_{i=1}^{T_{delay}} \{S_t + B_t\} \qquad (6.5)$$

where B_t is the busy time of the channel.

6.5   Performance Evaluation

This section applies to the previously introduced emergency extension to the MAC scheme and presents it in a simulated study. The basic settings for the simulation are provided in Table 6.1.

6.5.1   Performance Metrics and Simulation Parameters

The case study features a road segment of 1km length. As shown in Figure 6.3, the scenario considers vehicles moving in opposite directions at a different velocities. The simulation is implemented in the OMNeT++ 4.6 network simulator [Varga, 2001]. Vehicles drive at a velocity randomly varying in the interval $[20, 50]$km/h. The velocity is prone to road congestion, and fixed during the simulation. For instance, if there are fewer than 60 vehicles within the communication range (which is set to 200 meters),

the velocity interval is $[40, 50]$km/h. If the number of vehicles is between $[70, 80]$, then the velocity interval is set to $[30, 40]$km/h and for $[80, 100]$ vehicles, the speed range is between $[20, 30]$km/h. All messages have the same transmission range. A wireless data rate of 2Mbps is selected with a fixed packet duration of 2ms. The CSMA slot size is set to $20\mu s$ (microsecond) and the frame size is 10 slots.

6.5.2 Simulation Results

Performances of the proposed hybrid scheme (HyMAC) is compared with VeMAC [Omar et al., 2013] and the IEEE 802.11p (WAVE) standard protocols. The performance of these schemes are analyzed in terms of channels utilization, collision probability, successful transmission probability and throughput.
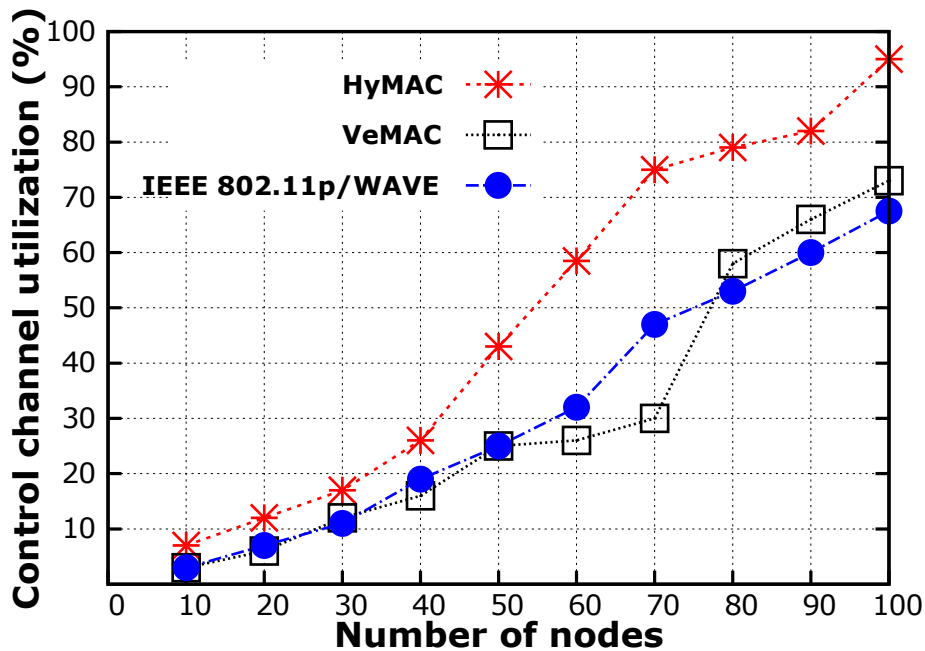
Figure 6.7: Control Channel Utilization vs. Number of nodes

Figure 6.7 shows the comparison of the utilization of the control channel in relation to the number of nodes deployed in the network area. A low number of nodes correlate with a low load on the CCH. The utilization of the CCH increases with the number of nodes. Compared with the VeMAC and with WAVE, HyMAC utilizes the CCH as much as possible. This leads to an improved service and control channel utilization using HyMAC scheme. At a node density of 100 the CCH utilization is more than 90% using HyMAC scheme. The main reason is that nodes contending for CCH are served by the SCH and therefore this load balance leads to the improved utilization of CCH channel as depicted in the figure.
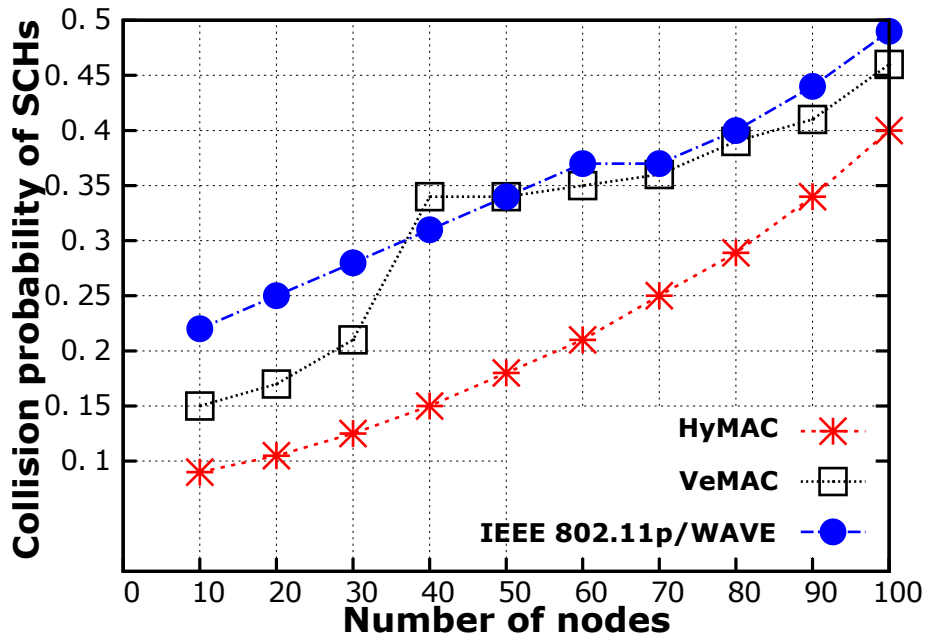
Figure 6.8: Collision Probability of SCHs, Emergency Mode

Figure 6.8 analyzes the collision probability within the SCHs. The collision probability in HyMAC is lower then its competitors When the packet tries to access an unavailable CCH it changes the network mode to benefit from the SCHs, unlike its competitors. Then, the SCHs stop all the ongoing infotainment messages immediately to increase the bandwidth for emergency messages. In fact, in case of HyMAC, the SCH channel utilization mainly depends on the CCH. In case of emergency, both the channels are utilized at maximum to guarantee the service, while in normal cases, the SCH is effectively utilized. Therefore, this results in lower probability of collisions for SCHs. VeMAC is dramatically influence when the number of nodes increase to 40 as it transmit large packets which create high overhead. The probability of collision of SCHs in case of VeMAC is also lower as it uses separate transceivers and considers the direction of vehicles.

Figure 6.9 compares the control channel utilization versus successful transmission probability for 100 nodes. Again, the proposed HyMAC outperforms VeMAC and IEEE 802.11p (WAVE). The CCH is utilized as far as possible, even for the service messages. The competitors are outperformed here for the reason that when the channel utilization is high, the channel becomes more busy. This affect the throughput as well and shown in Figure 6.10. The pulse technique discussed in Section 6.4.3 plays a vital role for the better performance of HyMAC compared to the other two comparative protocols.
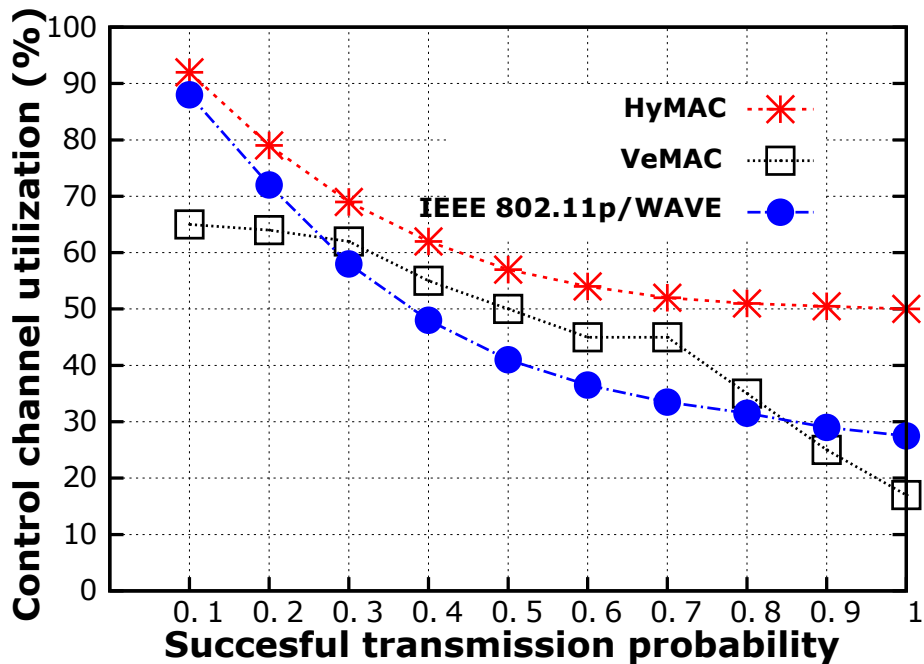
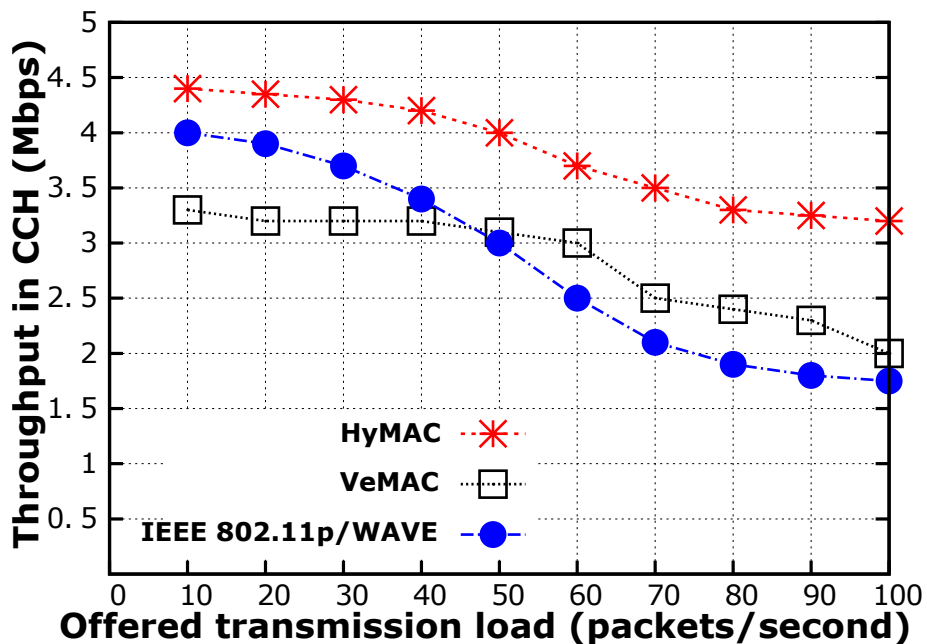Figure 6.9: CCH utilization vs. Successful Transmission Probability

Figure 6.10: Throughput (CCH) vs. Available Load

Figure 6.11 relates the average throughput versus the offered transmission load regarding the number of nodes. Again, the throughput of HyMAC is comparatively higher because of efficient channel utilization mechanism. While VeMAC and IEEE 802.11p perform similarly for low offered bandwidth, IEEE 802.11p outperforms VeMAC for high offered bandwidth. Yet, HyMAC outperforms both.

The packet delivery performance of these MAC schemes is also tested in denser network as shown in figure 6.12. As expected, the delivery
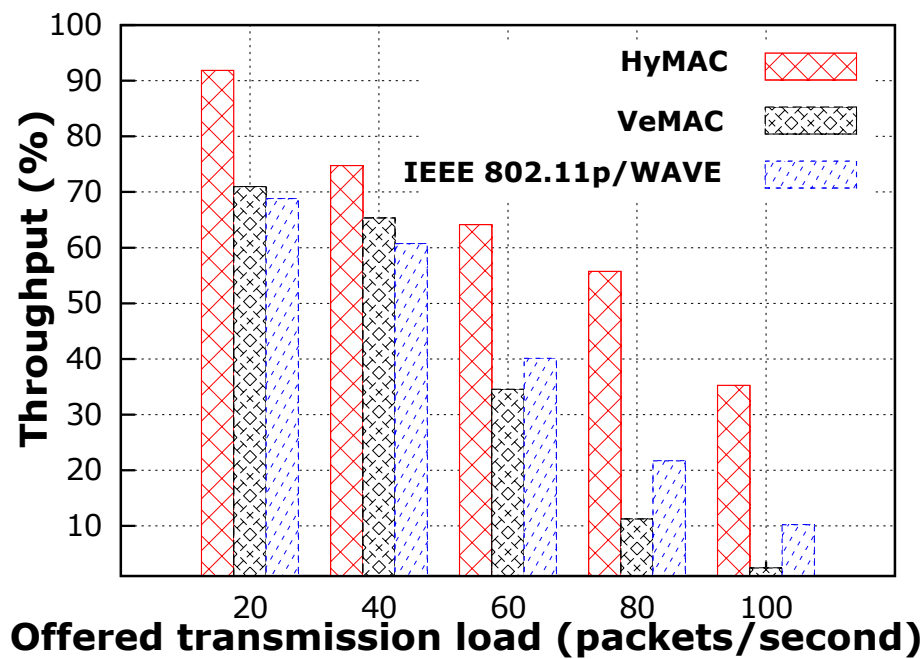
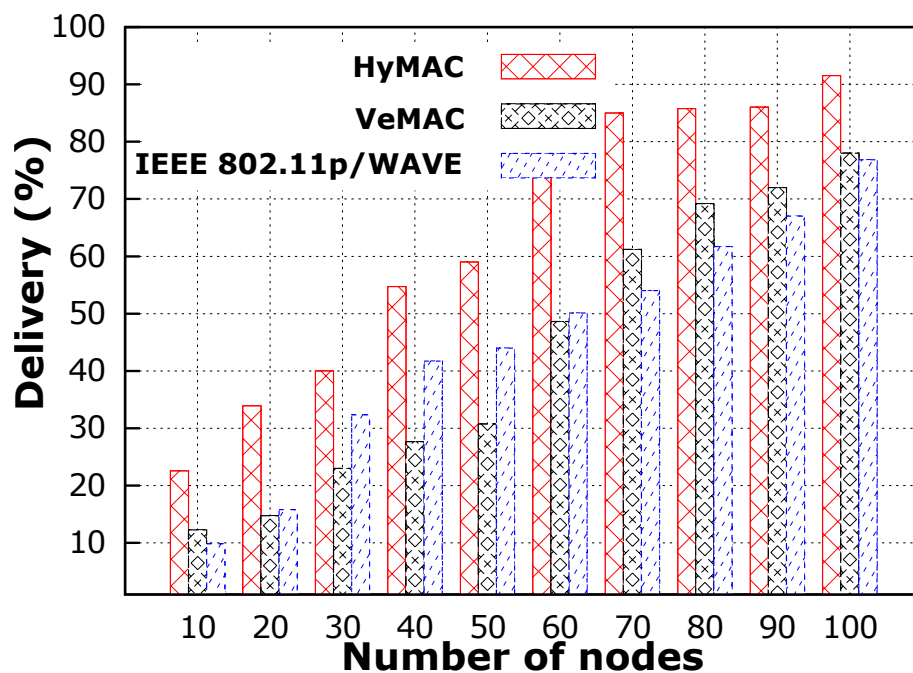Figure 6.11: Throughput vs. Available Transmission Load

Figure 6.12: Data Delivery Ratio vs. Node Density

ratio increases with the number of nodes for all the schemes however higher values are recorded for HyMAC because of its switching mechanism between the channels.

6.6   Chapter Summary

This chapter introduced a Hybrid MAC (HyMAC) scheme for VANETs that exploits the advantages of multiple channel access. HyMAC is tailored

for emergency communication in urban environments to improve the channel utilization of the Control Channel (CCH), and uniformly distribute the channel load on hijacked Service Channels (SCHs). The proposed scheme treats CCH and SCHs as CSMA and TDMA respectively. During the emergency situation, the local sub-networks change their modes from general to emergency mode to increase the probability for an urgent, timely and safety-critical message to arrive in time. The performance evaluation results show that the proposed hybrid scheme outperforms stat-of the-art competitors such as VeMAC and IEEE 802.11p (WAVE) in terms of collision probability, throughput and CCH utilization.

7. Conclusions and Future Directions

7.1 Introduction

Cooperative-Intelligent Transportation Systems (C-ITSs) are expected to bring a major revolution in advance road traffic communication systems such as Vehicular Ad-hoc Networks (VANETs). Through the ubiquitous Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) exchange information, different applications such as advanced road safety and traffic management can handle the road hazards detection and problematic traffic management system. Appropriately informing distant vehicles with respect to time and distance about the road incidents will permit the vehicles drivers to react accordingly, thereby improving the overall road safety and efficiency. However, the successful deployment of ITS facing various challenges such as technical, organizational and economical. Furthermore, the deployment of ITS is challenged by strict requirements of cooperative applications and adverse vehicular communication characteristics.

This chapter presents the thesis contents review and provides a summary of the conclusions and research contributions. It also highlights recommendations and suggestions for possible future studies from a new perspective in the VANETs environment.

7.2 Conclusion of the Contributions

Vehicular networks has given birth to a large variety of applications ranging from safety applications which aim to increase the user and vehicle safety to comfort applications like internet connection or file sharing. This thesis has addressed the problem of efficient data communication in VANETs.

For cooperative ITS applications, international efforts led to developing the IEEE 802.11p standard which allow direct transmissions between vehicles for direct communication with each other. This standard also enable the vehicles to communicate other vehicles which are out of their respective radio range by operating multihop transmissions. As, it is demanding for number of vehicular applications which aimed at transferring the data messages to distant vehicles. They can also be operated to distribute the data message to a set of vehicles over a relevance area. However, the effectiveness and efficiency of VANETs applications using multihop transmission vigorously depend on the adapted data routing VANETs protocols. The important challenges in VANETs communication come from its mobility, scalability, propagation conditions, redundancy, channel accessing, and dynamic topology changes etc.

This thesis has addressed the problems considering different protocols of network and MAC layers such as efficient data routing and data forwarding in VANETs, cooperative communication and channel accessing for the purpose of solving the mentioned issues. Through its contributions, it has demonstrated that the integration of VANET features e.g. road topology, real-time road traffic flow, presence of road obstacles etc. in the design of VANET protocols can lead to better performance. Furthermore, real time estimates of the multihop road connectivity can be measured in the VANET in a very channel efficient way. A summary and evaluation of these contributions are presented as follows:

- A novel Traffic Aware Segment-based Routing (TASR) for city-based environment has been presented that take the advantage of road topologies to improve the performance of routing in VANETs. TASR protocol uses real-time vehicular traffic information to create road-based paths between V2V. The proposed protocol consider the segment-based selection and the related vehicular traffic density. The road segment is chosen based on the proposed novel metric called Estimated Connectivity Degree (ECD). Furthermore, using the network simulator which provides the facility for the segment selection based on the deterministic way rather than probabilistic which is not always true in the real world experiments. To make the algorithm simple and understandable, the segment lengths were also not taken into account which is also not true in the real world. A modified geographical greedy forwarding algorithm is utilized to find forwarding nodes along the road segments that form these paths. Simulation were conducted using OMNeT++,

SUMO and Veins frameworks. TASR protocol shows superiority for selected settings and outperform existing approaches in terms of connectivity probability, average latency, average end-to-end data delivery ratio, average end-to-end delay, throughput and packet error rate. The reason behind is that TASR utilized forward data packets along the segments, not across the segments and take into account the real traffic on the road segments, which perform well in realistic vehicular environment in which line of sight not exist because of buildings and other road characteristic such as dead end segments. Furthermore, The simulation results demonstrate that distributed applications that generate a moderate amount of traffic can be successfully implemented in VANETs.

- A new novel MAC protocol named Cooperative and Network Coding MAC (CNC-MAC) protocol is presented covering the transmission failure issues utilizing NC technique. Furthermore, Contention Window (CW) adjustment scheme is proposed according to the nodes velocity. In this protocol only 1 source node, 1 destination node and 3 relay nodes were considered, but it is more important to analyse for the congested area (e.g. city) as well which is major point and should be consider in the extended version. The proposed CNC-MAC protocol is evaluated by using time-driven C++ simulator against with its counterpart conventional Cooperative Automatic Repeat ReQuest MAC (CARQ-MAC) protocol and checked that how the throughput, packet error rate, packet delivery ratio and latency are effected against velocity. CNC-MAC protocol exploits the advantages of cooperative communication and network coding techniques to outperform the CARQ-MAC as selected. CNC-MAC allows to enhance throughput up to 80%-90% by minimizing the number of transmissions. Furthermore, CNC-MAC MAC performs better under high mobility and significantly reduces the number of packet loss. Another contribution is also possible, if CNC-MAC can be used together with TASR, as in TASR always the precise and complete data required. Due to the building and other shielding objects the data may be interrupted, in that case CNC-MAC is highly demanded for TASR.

- A Hybrid MAC (HyMAC) scheme for VANETs is proposed that exploits the advantages of multiple channel access. HyMAC is tailored for emergency communication in urban environments to improve the channel utilization of the Control Channel (CCH), and uniformly dis-

tribute the channel load on hijacked Service Channels (SCHs).The proposed scheme treats CCH and SCHs as Carrier Sense Multiple Access (CSMA) and Time Division Multiple Access (TDMA) respectively. During the emergency situation, the local sub-networks change their modes from general to emergency mode to increase the probability for an urgent, timely and safety-critical message to arrive in time. The performance evaluation results show that the proposed hybrid scheme outperforms stat-of the-art competitors such as VeMAC and IEEE 802.11p (WAVE) in terms of collision probability, throughput and CCH utilization.

7.3   Future Directions

The analysis and findings presented in this thesis report have shown a good performance of the proposed TASR protocol as well as its impressive proposed connectivity metric ECD. Nevertheless, several possible future research directions are open up in which the work done in this thesis could be extended.

- It is essential to further study in TASR that how vehicles select an alternative driving route when they are informed about an incident if a real road network layout is utilized. Furthermore, it can also be investigated that how the vehicles statistics such as vehicles density and average speed in the chosen alternative path change due to the incident on the previous path. Also, the impact of radio transmission regions can be investigate with different values on the congested segments.

- In order to investigate the road connectivity of different segments, it is beneficial to use model checking techniques. In this sense, Probabilistic Model Checker (PMC) is a formal method which can be utilized to verify the correctness of different properties of interest. In the proposed scenario, it can formalize the proposed protocol by Markov models, such models can be analyzed by PMC i.e. , PRISM [PRI,], UPPAAL [UPP,] the quantitative results will give the idea that how much the connectivity is stable. Furthermore, this technique can be used for CNC-MAC protocol as well according to their properties.

- The further optimization of HyMAC scheme that how to access the slots on the service channels (SCHs) according to IEEE 1609.4 standard and develop a theory for proving timely delivery under the given condition. In addition, it is aimed to provide a complete mathematical

framework that will be able to investigate the performance of proposed hybrid scheme.

To conclude, this thesis highlighted the performance benefits of including the characteristics of VANETs in the network and MAC protocols. This main results and the individual thesis contributions can be leveraged in future real-world deployment of VANETs to enable a large set of applications ranging from dynamic route planning to file sharing between moving vehicles.

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List of Figures

List of Abbreviations

2G	Second Generation
3G	Third Generation
A-STAR	Anchor-based street and traffic Aware Routing
AANET	Airborn Ad-hoc Network
ABCR	Affinity Based Clustering Routing
AF	Amplify and Forward
AGF	Advance Greedy Forwarding
AGF	Advanced Greedy Forwarding
AODV	Ad-hoc On-demand Distance Vector
AOMDV	Ad-hoc On-demand Multipath Distance Vector
ARQ	Automatic Repeat Request
ARQ	Automatic Repeat Request
ASV	Advanced Safety Vehicle Program
AWGN	Additive While Gaussian Noise
BROADCOMM	Broadcast Communication
BSS	Basic Service Set
C-2-C	Car-to-Car
C-ITS	Cooperative Intelligent Transportation System

C2C-CC	C2C-Communication Consortium
CAM	Cooperative Awareness Message
CAR	Connectivity-Aware Routing
CBDRP	Cluster-based Directional Routing Protocol
CBF	Contention Based Forwarding
CBR	Cluster Based Routing
CC	Coded Cooperation
CC	Cooperative Communication
CCH	Control Channel
CDF	Cumulative Distribution Function
CH	Cluster Head
CNC	Cooperation and Network Coding
CooPerCom	Cooperative Perception and Communication
CSMA	Carrier Sense Multiple Access
CSMA	Carrier Sense Multiple Access
CTS	Clear To Send
CVIS	Cooperative Vehicles and Infrastructure Systems
CW	Contention Window
CW	Contention Window
DCF	Distributed Coordination Function
DF	Decode and Forward
DIFS	DCF Inter-frame Space
DRG	Distributed Robust Geocast
DSDV	Destination Sequenced Distance Vector
DSR	Dynamic Source Routing

DSRC	Dedicated Short Range Communication
DSSS	Driving Safety Support Systems
DTN	Delay Tolerant Network
E-payment	Electronic-payment
ECD	Estimated Connectivity Degree
EDC	Expected Connectivity Degree
EDD	Expected Disconnection Degree
ETC	Electronic Toll Collection
ETSI	European Telecommunications Standards Institute
EVITA	E-safety Vehicle Intrusion Protected Applications
FEC	Forward Error Correction
FEC	Forward Error Correction
FSR	Fisheye State Routing
GeoDTN	Geographic Delay Tolerant Networks
GeOpps	Geographical Opportunistic Routing
GPCR	Greedy Perimeter Coordinator Routing
GPCR	Greedy perimeter coordinator routing
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
GPSR	Greedy Perimeter Stateless Routing
GpsrJ+	Greedy Perimeter Stateless Routing Junction+
GSR	Geographic Source Routing
GSR	Geographic Source Routing
GyTAR	Greedy Traffic Aware Routing

HN	Head Node
HyMAC	Hybrid MAC
INTERSAFE	Intersection Safety
ITS	Intelligent Transportation System
IVC	Inter Vehicle Communication
IVG	Inter-Vehicular Geocast
JARR	Junction-based Adaptive Reactive Routing
JBR	Junction-Based Routing
LOUVRE	Landmark Overlays for Urban Vehicular Routing Environments
LTE	Long-Term Evolution
MAC	Medium Access Control
MANET	Mobile Ad-hoc Network
MITI	Ministry of International Trade and Industry
MP	Meeting Point
MPT	Ministry of Posts and Telecommunications
MRC	Maximum Ratio Combining
MRC	Maximum Retransmission Count
MURU	MUltihop Routing protocol for Urban VANETs
N2N	Next-to-Next
N2N	Next-to-Next
Nav	Navigator
NC	Network Coding
NCC	Network Coding-based Cooperative
NED	Network Description
NETGEN	Network Generator

NICP	Network Information Collection Packet
NLoS	Non Line of Sight
NoW	Network on Wheels
NP	Nearest Point
NPA	National Police Agency
OBU	On-Board Unit
ODI	On-board Diagnostic Interface
OSM	OpenStreetMap
PATH	Partners for Advanced Transit and Highways
PDA	Personal Data Assistant
PDR	Packet Delivery Ratio
PG	Preferred group
PGB	Preferred Group Broadcasting
PHY	Physical
QoS	Quality of Service
R-AOMDV	On-demand Multipath Distance Vector with Retransmission
R&D	Research and Development
ROVER	Reliable Geographical Multicast Routing
RREP	Route Reply
RREQ	Route Request
RSU	Road Side Unit
RTS	Request To Send
SCHs	Service Channels
SI	Segment Information
SIFS	Short Inter Frame Space

SNR	Signal-to-Noise Ratio
SRB	Selective Reliable Broadcast
STBR	Street Topology Based Routing
SUMO	Simulation of Urban MObility
TASR	Traffic Aware Segment-based Routing
TDMA	Time Division Multiple Access
TO-GO	TOpology-assist Geo-Opportunistic
TORA	Temporally Ordered Routing Algorithm
TraCI	Traffic Control Interface
UMB	Urban Multihop Broadcast
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
VADD	Vehicle Assisted Data Delivery
VANET	Vehicular Ad-hoc Network
VDLA	Vehicle Density and Load-Aware
VICS	Vehicle to Information and Communication System
VII	Vehicle Infrastructure Integration
VoIP	Voice over IP
VSC	Vehicle Safety Communication
WAVE	Wireless Access in Vehicular Environment
WBSS	WAVE Basic Service Set
WILLWARN	Wireless Local Danger Warning
ZOF	Zone Of Forwarding
ZOR	Zone Of Relevance
ZRP	Zone Routing Protocol