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Reliable Message Dissemination in Mobile Vehicular Networks

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Résumé

Les réseaux véhiculaires accueillent une multitude d'applications d'info-divertissement et de sécurité. Les applications de sécurité visent à améliorer la sécurité sur les routes (éviter les accidents), tandis que les applications d'info-divertissement visent à améliorer l'expérience des passagers. Les applications de sécurité ont des exigences rigides en termes de délais et de fiabilité ; en effet, la diffusion des messages d'urgence (envoyés par un véhicule/émetteur) devrait être fiable et rapide. Notons que, pour diffuser des informations sur une zone de taille plus grande que celle couverte par la portée de transmission d'un émetteur, il est nécessaire d'utiliser un mécanisme de transmission multi-sauts. De nombreuses approches ont été proposées pour assurer la fiabilité et le délai des dites applications. Toutefois, ces méthodes présentent plusieurs lacunes.

Cette thèse, nous proposons trois contributions. La première contribution aborde la question de la diffusion fiable des messages d'urgence. A cet égard, un nouveau schéma, appelé REMD, a été proposé. Ce schéma utilise la répétition de message pour offrir une fiabilité garantie, à chaque saut, tout en assurant un court délai. REMD calcule un nombre optimal de répétitions en se basant sur l'estimation de la qualité de réception de lien dans plusieurs locations (appelées cellules) à l'intérieur de la zone couverte par la portée de transmission de l'émetteur. REMD suppose que les qualités de réception de lien des cellules adjacentes sont indépendantes. Il sélectionne, également, un nombre de véhicules, appelés relais, qui coopèrent dans le contexte de la répétition du message d'urgence pour assurer la fiabilité en multi-sauts. La deuxième contribution, appelée BCRB, vise à améliorer REMD ; elle suppose que les qualités de réception de lien des cellules adjacentes sont dépendantes ce qui est, généralement, plus réaliste. BCRB utilise les réseaux Bayésiens pour modéliser les dépendances en vue d'estimer la qualité du lien de réception avec une meilleure précision. La troisième contribution, appelée RICS, offre un accès fiable à Internet. RICS propose un modèle d'optimisation, avec une résolution exacte optimale à l'aide d'une technique de réduction de la dimension spatiale, pour le déploiement des passerelles. Chaque passerelle utilise BCRB pour établir une communication fiable avec les véhicules.

Mots clés: messages d'urgence, Internet des véhicules, fiabilité, diffusion, multi-sauts.

Abstract

Vehicular networks aim to enable a plethora of safety and infotainment applications. Safety applications aim to preserve people's lives (e.g., by helping in avoiding crashes) while infotainment applications focus on enhancing the passengers' experience. These applications, especially safety applications, have stringent requirements in terms of reliability and delay; indeed, dissemination of an emergency message (e.g., by a vehicle/sender involved in a crash) should be reliable while satisfying short delay requirements. Note, that multi-hop dissemination is needed to reach all vehicles, in the target area, that may be outside the transmission range of the sender. Several schemes have been proposed to provide reliability and short delay for vehicular applications. However, these schemes have several limitations. Thus, the design of new solutions, to meet the requirement of vehicular applications in terms of reliability while keeping low end-to-end delay, is required.

In this thesis, we propose three schemes. The first scheme is a multi-hop reliable emergency message dissemination scheme, called REMD, which guarantees a predefined reliability , using message repetitions/retransmissions, while satisfying short delay requirements. It computes an optimal number of repetitions based on the estimation of link reception quality at different locations (called cells) in the transmission range of the sender; REMD assumes that link reception qualities of adjacent cells are independent. It also adequately selects a number of vehicles, called forwarders, that cooperate in repeating the emergency message with the objective to satisfy multi-hop reliability requirements. The second scheme, called BCRB, overcomes the shortcoming of REMD by assuming that link reception qualities of adjacent cells are dependent which is more realistic in real-life scenarios. BCRB makes use of Bayesian networks to model these dependencies; this allows for more accurate estimation of link reception qualities leading to better performance of BCRB. The third scheme, called RICS, provides internet access to vehicles by establishing multi-hop reliable paths to gateways. In RICS, the gateway placement is modeled as a k-center optimisation problem. A space dimension reduction technique is used to solve the problem in exact time. Each gateway makes use of BCRB to establish reliable communication paths to vehicles.

Key words: emergency message dissemination, Internet of Vehicles, Reliability, broadcast, multi-hop.

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List of abbreviations

ACK	ACKnowledgement
AIFS	Arbitrary Inter-Frame Spacing
BCRB	Bayesian networks and unipolar orthogonal Code based Reliable multi-hop Broadcast
BN	Bayesian Network
BR	Broadcast Reliability
BSS	Basic Service Set
BSSID	Basic Service Set Identifier
CCH	Control Channel
CCI	Control Channel Interval
CDS	Connected Dominating Set
CPF	Cooperative Positive orthogonal code-based Forwarding
CSMA/CA	Carrier Sense Multiple Access/Collision Avoidance
CTB	Clear To Broadcast
CTS	Clear To Send
CW	Contention Window
DCF	Distributed Coordination Function
DSRC	Dedicated Short Range Communication
EDCA	Enhanced Distributed Channel Access
FCC	Federal Communication Commission
FS	Forwarders Selection
GML	Graphical Model Learning
GPS	Geographic Positioning System
IEEE	Institute of Electrical and Electronics Engineers
ITS	Intelligent Transportation Systems
LLC	Logical Link Control
LTE	Long Term Evolution
MAC	Medium Access Layer

MRL	MAC Repetition Layer
M-HRB	Multi-Hop Reliable Broadcast
OBU	On-Board Unit
OCB	Outside the Context of BSS
OFDM	Orthogonal Frequency Division Multiplexing
PC	Peter-Clark
PDP	Packet Delivery Probability
PHY	Physical Layer
PLCP	Physical Layer Convergence Procedure
PMD	Physical Medium Dependent
POC-MAC	Positive Orthogonal Code based MAC
PPDU	Physical Protocol Data Unit
PRR	Packet Reception Rate
QoS	Quality of Service
REMD	Reliable Emergency Message Dissemination
RICS	Reliable Internet access System
RSSI	Received Signal Strength Indication
RSU	Road Side Unit
RTB	Request To Broadcast
RTS	Ready To Send
SAPF	Speed Adaptive Probabilistic Flooding
SCH	Service Channel
SIFS	Short Inter-Frame Space
TDC	Training Data Collection
UPOC	Uni-Polar Orthogonal Code
V2V	Vehicle-to-Vehicle
V2I	Vehicle-to-Infrastructure
VANET	Vehicular Ad hoc Network
WAVE	Wireless Access for Vehicular Environment

Dedication

My dear parents

For your patience, your kindness, and prayers

I dedicate this work as a token of my eternal gratitude and my profound respect

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Chapter 1
Introduction

1.1. Introduction

The exponential growth of population and business activities is yielding to severe transportation problems, such as loss of lives (e.g., because of accidents) and traffic congestion. Careful city planning does not scale well over time with an unexpected road usage. Land resources are limited in several countries making it difficult to build new infrastructure (e.g., bridges and highways). More recently, several vehicle safety devices (e.g., seat belts and airbags) have been produced for post-crash live saving goals.

Still, road accidents are considered one of the main causes of death. About 1,700,000 accidents cause over 40,000 deaths and more than 1,300,000 injuries each year in Europe [1]. More than 23% of these traffic fatalities occur due to high-speed, adverse weather and road conditions [1]. To enhance road safety, the recent focus is to provide real time early warning systems (pre-crash warning systems) to alert drivers about dangers ahead. The objective of such systems is to give drivers enough time to undertake early counter measures.

Figure 1.1 depicts a pre-crash warning system. Three vehicles move at speed of 115 km/h (32 m/s) and with an inter-vehicle spacing of 1 s (32 m). If the front vehicle starts hard-braking with deceleration of 4 m/s^2, the second vehicle's driver reaction time is 1,5 s (the third vehicle's driver reaction time is 3s). Without a pre-crash warning, driver 2 and vehicle 3 will slam on the brakes only after seeing the brake lights of the first vehicle, resulting in a 3-vehicle pileup accident. However, employing a pre-crash warning system can reduce (or avoid) the severity of the pileup accident. Indeed, if a warning notification about the hard-braking is conveyed with the minimum possible delay to vehicle 3, such a crash can be avoided [140]. Furthermore, the earlier drivers 2 and 3 are warned of the imminent vehicle crash, the less severe the accidents can be.

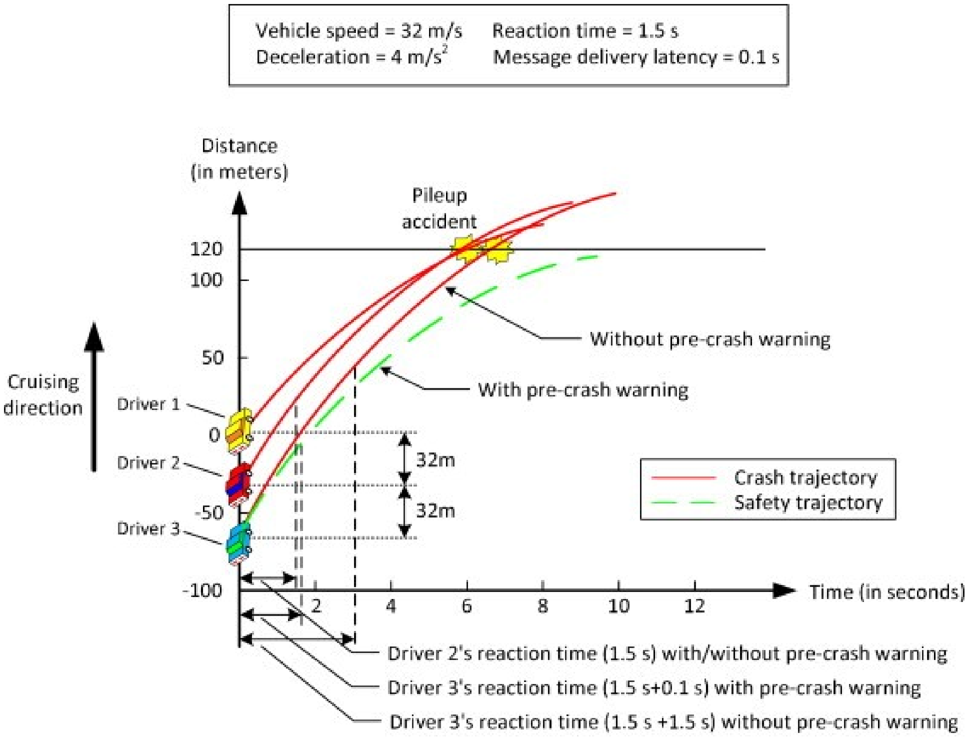

Figure 1.1. Illustration of a pre-crash warning system [140]

Intelligent Transportation Systems (ITS) using wireless communications and sensors are suggested to improve road safety. Here, roads and vehicles become not only a transportation platform but also a communication platform. Vehicular Ad hoc Networks (VANET) represent the key technology of ITS by enabling wireless communication among vehicles; indeed, it has been reported that VANETs have the potential to address more than 79% of all crashes involving unimpaired drivers. In VANET, every vehicle is equipped with a wireless communication device that enables Vehicle-to-vehicle (V2V) communication and Vehicle-to-Infrastructure (V2I) communication. Both V2V and V2I communications are standardized by the dedicated short-range communication DSRC standard [2].

The rest of the chapter is organized as follows. Section 1.2 presents V2V and V2I communication modes, the DSRC standard in the U.S, characteristics of VANETs and a sample of applications that can be implemented in VANETs. Section 1.3 describes our motivation and problem statement. Section 1.4 presents thesis contributions. Section 1.5 presents thesis organisation.

1.2. Vehicular Ad Hoc Networks

1.2.1. V2V and V2I communication modes

VANET architecture supports V2V and V2I communications. V2V communication allows the communication among neighboring vehicles. V2I communication allows the communication between vehicles and fixed roadside units (RSUs). RSUs are installed at fixed roadside locations. Each vehicle is equipped with a wireless communication device, called an on-board unit (OBU), to form wireless communication links between vehicles (or RSUs). Hence, OBUs communicate with other neighboring OBUs or with neighboring RSUs. RSUs have higher radio coverage than vehicles. One of the main benefits of RSU infrastructure is to relieve poor network connectivity (e.g., RSUs can increase the overall coverage of a vehicular network and enhance network performance (i.e., delay) between disconnected vehicles) [8]. RSUs are connected to the Internet via either wireline or wireless networks. In addition, by establishing connection with an RSU, a vehicle can access the Internet (see Figure 1.2).

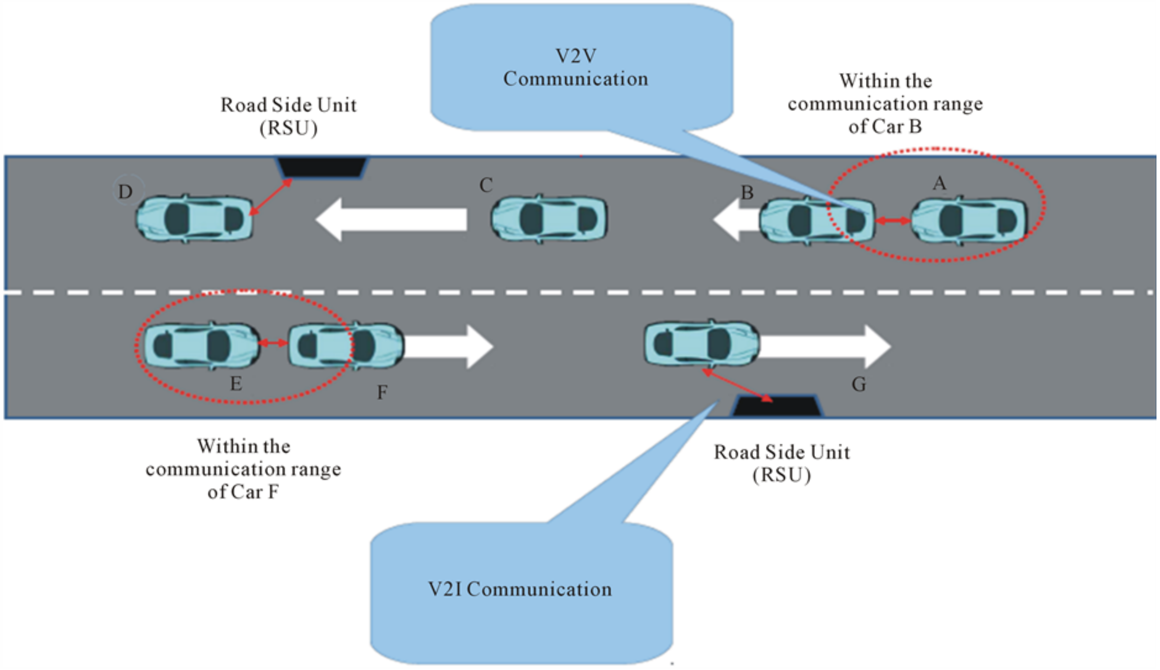

Figure 1.2 Vehicular Ad Hoc Network (V2V and V2I communications)

The radio communication range varies based on the transmission power of the transceiver [2]. The maximum radio communication range of an OBU device is smaller than 1 km. If a message needs to be disseminated to nodes[2] beyond the radio range, blind flooding (i.e., every vehicle within a target area for message transmission retransmits the message) extends the radio coverage range of a node by multi-hop links. In dense networks, *flooding* degrades considerably the network performance (e.g., due to high packet collisions). The alternative techniques are non-flooding. These techniques, called message dissemination, allows only some vehicles, called "*forwarders*", to retransmit the message, which is reviewed in Chapter 2 of this dissertation.

1.2.2. DSRC Overview

Dedicated Short Range Communication (DSRC) [2] is the emerging wireless technology for communication between OBUs and RSUs. The term "Dedicated" refers to the fact that the Federal Communications Commission (FCC) in the U.S, allocated 75 MHz of licensed spectrum in the 5.850–5.925 GHz frequency band, for vehicular communication [3]. The term "Short Range" conveys that communication takes place over short range radio links (i.e., hundreds of meters). The primary motivation for DSRC deployment is crash-prevention. DSRC frequency band is divided into one Control Channel (CCH) and six Service Channels (SCHs). Safety messages are exchanged on CCH. Figure 1.3 shows the protocol stack for DSRC communication in the U.S.

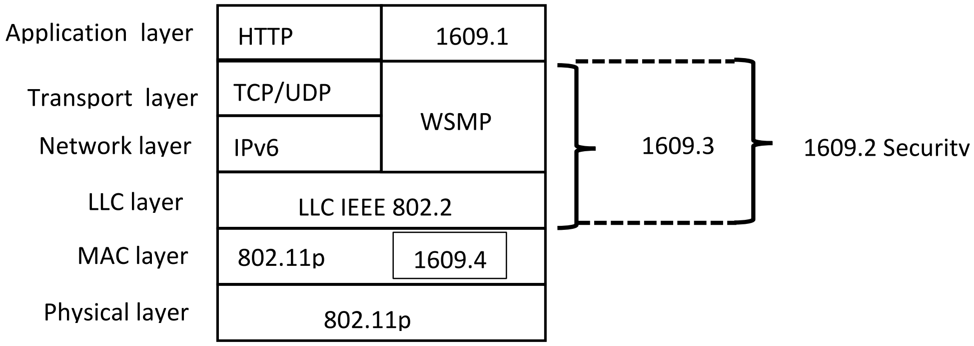

Figure 1.3. Layered DSRC architecture in the U.S.

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[2] Nodes designate either vehicles or RSUs

At the Physical (PHY) layer and medium access control (MAC) layer, DSRC uses IEEE 802.11p which is a modified version of IEEE 802.11 (WiFi) standard. In the next subsections, we present the DSRC Physical (PHY) layer and the DSRC Medium access control (MAC) layer.

1.2.2.1. Physical Layer

The physical layer of IEEE 802.11p is similar to IEEE 802.11as, with some adaptations for VANET characteristics. DSRC/IEEE 802.11p PHY reduces the signal band from 20MHz to 10MHz. As a result, the values of physical parameters (e.g., guard interval and duration of a data symbol) for IEEE 802.11p are doubled compared to the IEEE 802.11a PHY. The DSRC PHY protocol is defined in IEEE 802.11. The physical layer protocol is divided into two sublayers: the physical medium dependent (PMD) sublayer and the physical layer convergence procedure (PLCP) sublayer. PMD interfaces directly with the wireless medium. It uses the familiar orthogonal frequency division multiplexing (OFDM) technique, which was originally added to 802.11 in the 802.11a amendment. PLCP defines the mapping between the MAC frame and the basic PHY layer data unit. In a transmitter, PLPC processes the bytes in a MAC frame in order to be transmitted into OFDM symbols for transmission over the air by PMD. PLPC adds PHY layer overhead to the MAC frame to create the PHY Protocol Data Unit (PPDU). The MAC sublayer passes 3 parameters to PLPC: (1) length of the MAC frame; (2) transit data rate; and (3) transmit power. In a receiver, PLPC performs the inverse function to extract the MAC frame from PPDU. Furthermore, PLPC provides the received signal strength interference (RSSI). When PLPC requests PMD to transmit a frame, the PMD sublayer performs the OFDM modulation and transmits PPUD over the air. The PMD receiver performs the demodulation. The PMD sublayer passes RSSI with the received frame up to the PLPC sublayer. At the receiver, 802.11p does not modify the sensitivity requirement which is a function of the data rate of the packet. For 10 MHz, minimum sensitivity levels vary from -85 dBm at 3Mb/s to -68dBm at 27Mb/s. DSRC on 10 MHz channels is more suited to delay and Doppler effects in a vehicular environment.

1.2.2.2. MAC Sublayer

The MAC layer of IEEE 802.11p is based on IEEE 802.11a. Particularly, for V2V, DSRC defines a new type of 80211 communication, Outside the Context of a Basic service set (OBC), to cope with VANET high mobility (e.g., short-duration communication link in case of two vehicles with opposing driving directions). OBC does not require neither authentication nor association when exchanging data frames. To distinguish frames sent in OCB mode, 802.11p sets the value of Basic Service Set (BSS) identifier (BSSID) field in the data frame header to 0xFFFFFF, also known as wildcard value. IEEE 802.11p utilizes the Enhanced Distributed Channel Access (EDCA) mechanism to provide service differentiation. The basic mechanism of sharing the medium between vehicles relies on the Distributed Coordination Function (DCF) of CSMA/CA. IEEE 802.11p does not alter CSMA/CA rules in the 802.11 [2] (the principles of "carrier sensing" and "collision avoidance"); carrier sensing is achieved through Clear Channel Assessment (CCA) and/or Network Allocation Vector (NAV). Collision avoidance is achieved using a back-off procedure. In a simplest communication scenario under CSMA/CA, if a vehicle has a frame to send, it first senses the wireless medium for Distributed Inter-frame Space (DIFS). If the medium is idle, the vehicle begins transmission of its frame. If the medium is busy, the vehicle performs a random back-off to wait before transmission. The countdown begins when the medium becomes idle. The above mechanism applies to both broadcast and unicast frames. Besides, EDCA enables 4 Quality of Service (QoS) classes by prioritizing data traffic within each node. Hence, each node maintains four queues. These queues have different Arbitrary Inter Frame Spacing (AIFS) and different back-off parameters; the higher the priority, the shorter AIFS. Each transmission queue of an Access Category (AC) operates as an independent DCF station (STA). Figure 1.4 shows the basic channel access procedure in DCF. Basically, in unicast communication, the sender transmits a packet and waits for an acknowledgment (ACK). If no ACK is received, a back-off procedure is invoked before a retransmission is allowed. For every attempt to send a packet, the size of the contention window (CW) is doubled from its initial value (CW_{min}) until a maximum value (CW_{max}) is reached. This enables to separate the nodes that want to send at the same time. After a successful transmission (or when the maximum number of channel access attempts is reached), the contention window is reset to its initial value. Furthermore, vehicles can employ RTS/CTS control packets handshake to combat the hidden terminals problem. However, in broadcast communication, a frame is not acknowledged and is sent only once.

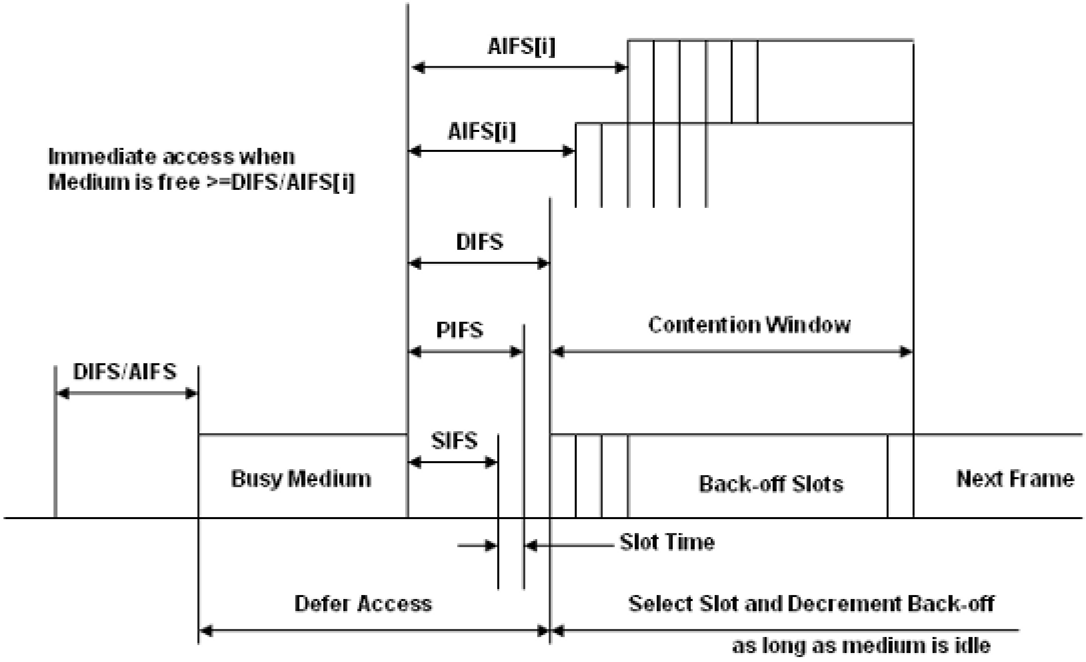

Figure 1.4. IEEE 802.11 distributed coordination function (DCF)

Besides, broadcast frames cannot use the RTS/CTS handshake making them prone to the hidden terminal problem. EDCA/DCF lacks deterministic QoS guarantee for broadcast communication. This issue is investigated in Chapters 3 and 4.

1.2.3. VANET characteristics

In this Section, we start by describing radio propagation issues, in urban vehicular networks (e.g., presence of buildings), and interferences; then, we present key characteristics of vehicular networks.

✓ *Radio propagation*

Here, we consider direct communication between one transmitter and one receiver. The characteristics of radio signals change over time and space. Signal propagation is influenced by three basic physical phenomena [139]:

(a) Reflection, which occurs when a wave hits an object of very large dimension compared to the wavelength of the wave. These objects can be buildings or walls. If a wave is reflected, it changes its direction;

(b) Diffraction, which occurs if a wave hits an object that has sharp irregularities (e.g., building edges). In this case, many secondary waves occur that continue propagating;

(c) Scattering, which occurs if the propagation medium contains a high number of objects that are small compared to the wavelength, e.g., street signs. These objects split the wave into several ones. At the receiver, several of the waves arrive and they interfere with each other resulting in interferences between different propagation paths of one transmitted signal [139].

These effects are caused by the physical environment (e.g., frequency, distance, antenna heights, atmospheric conditions, and the presence of buildings) in which the signal propagates. To describe these effects on the signal, three types of radio propagation models are used [139]: (i) large-scale path loss; (ii) shadowing or large-scale fading; and (iii) small-scale fading. A possible way to describe the reception characteristics of a signal lies in subsequently applying mathematical descriptions of the three models to the transmitted signal: first, the signal attenuation due to the path loss is calculated, then, shadowing effects are added, and finally, the effects of fading are applied [139].

✓ *Interference*

Here, we consider multiple transmissions in the network. Basically, there are two sources of interference on a communication channel from the perspective of a receiving node (We focus on the common control channel (CCH)): (a) *Multi-path interference*; and (b) *Multi-user interference*.

- *Multi-path interference* is the fact that a transmission follows multiple paths, as explained in the previous paragraph.
- *Multi-user interference* is the fact that multiple transmissions overlap on the same channel [139]. Multi-user interference occurs for two main raisons: (a) two senders that are geographically close to each other (in the radio ranges of each other) access the channel at the same moment in time. This interference can be mitigated using medium access schemes that are based on CSMA/CA. Indeed, using CSMA/CA, the channel may be accessed only if a node that wants to transmit a message does not sense any other transmission on the channel (see Section 1.2.2.2 for details about the EDCA/DCF scheme). The use of a random number of back-off slots reduces the probability that two senders that are geographically close to each other access the channel at the same moment. However, the back-off procedure cannot ideally avoid such simultaneous access

in broadcast transmission, resulting in collisions. This phenomenon is serious in multi-hop broadcasting that uses flooding (see. Section 2.2 of Chapter 2 for more details). Non-flooding techniques in consequence reduce the number of transmitters (forwarders) which can reduce probability of transmitting on the same slot; and (b) hidden terminal, defined as the access to the channel during the transmission of another packet. Hidden terminal is the primary cause of multi-user interference. Indeed, the CSMA/CA decides on whether the channel is in use or not by measuring the signal power on the wireless channel. The received power may become low over distance due to path loss (In chapter 3, we provide a method to compute signal power attenuation rate caused by background traffic at each receiver and we find out that this rate is proportional to the packet collision rate that occurs at same receiver). As a result, a node may sense the channel idle while another transmission that has a low reception power is ongoing at the specific receiver. The node, thus, decides to transmit although there is an ongoing transmission resulting in collision at a receiver positioned between the two transmitters [139].

✓ *Mobility*

VANET is a highly dynamic and mobile environment. Vehicles have mobile characteristics (i.e., each driver has its own moving way to reach an individual geographical location). Yet, the degree of freedom is limited by the road network, traffic rules and the behavior of other vehicles on the same road. The mobility of nodes affects communication, as radio propagation characteristics and network topology continuously change [139].

✓ *Distributed decentralized system*

In VANET, a huge number of mobile vehicles and stationary RSUs participate in the communication. Such a communication system is distributed and decentralized. Hence, a centralized control that provides management and coordination functionality is not possible. Instead, immediate and direct communication among all nodes is established and provided in a decentralized manner. Such a decentralized control leads to interferences of uncoordinated transmitters [139].

✓ *Broadcast communication*

Data traffic generated by safety applications is broadcast traffic. Broadcast means that the transmitted data (e.g., crash warning) is not addressed to one specific vehicle, but to all vehicles positioned in the surrounding of the transmitter. The challenge of data dissemination/broadcast is that a reception by every node within a specified surrounding cannot be guaranteed as there is no suitable way to acknowledge the reception of broadcast messages. Even if acknowledgement schemes are used, it will not be possible to ensure that every possible receiver gets the message. This is due, in part, to the fact that there is no information on how many nodes are potential (good) receivers. Consequently, reliability of transmissions cannot be guaranteed for broadcast communication. This makes the impact of interference even more severe in broadcast transmissions.

1.2.4. VANET Applications

This section overviews vehicular applications, several user cases and their associated QoS requirements. ITS applications can be classified into three categories: (a) road safety applications; (b) traffic efficiency and management applications; and (c) infotainment applications.

1.2.4.1 Road Safety Applications

Safety applications are employed to decrease the probability of crashes. The U.S. Vehicle Safety Communications Consortium has identified more than 75 application scenarios enabled by DSRC [4]. These applications can be accomplished by sharing, between vehicles and RSUs, (a) periodic messages (also called beacons): they are preventive safety messages used, for example, to predict collisions. Note that beacons can be also used by non-safety applications (e.g., road traffic control). Exchange of beacons makes vehicles aware of their environment; indeed, beacons contain information about the state of the sending vehicle (e.g., position, direction, and speed); and (b) event-driven messages (also called emergency or safety messages): they are generated due to the detection of unsafe situations (e.g., a car crash). More specifically, a vehicle generates an emergency message on detecting a danger. A vehicle is defined as the source node when it detects the danger on the road. The emergency message should be delivered to all nodes in the target area, also called risk zone[3], exposed to the potential danger as quickly as possible. The risk zone is extended behind the source vehicle along the road. All vehicles in the risk zone should be notified ahead of time, before they reach the potential danger location, to allow them to take action in time (e.g., slow down or brake). Emergency messages are

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[3] Risk zone designates the target area of an emergency message

disseminated in a broadcast fashion since their content is beneficial to all vehicles in the risk zone. Safety applications have strict reliability and delay requirements (See Table 1.1).

Table 1.1. Example of vehicular safety applications: communication requirements [5][136]

Safety application	Transmit mode	Range	Max. Latency (ms)	Reliability requirement
Over taking vehicle warning	Periodic	≤ 250	1000	High
Head on collision warning	Periodic	≤ 250	200	High
Intersection collision warning	Event-driven	≤ 300	100	High
Post-crash Notification	Event-driven	≤ 300	500	High
Cooperative collision warning	Event-driven	≤ 300	100	High

In the following, we present some examples of safety applications and their use cases.

- ✓ *Overtaking vehicle warning (OVW)*

OVW [137] [138] aims at preventing collision between vehicles in an overtake situation, in urban roads. A possible use case of OVW application is depicted in Figure 1.5; vehicle 1 is willing to overtake vehicle 3. A Powered Two Wheeler (PTW) 2 is already doing an overtaking maneuver on vehicle 3. Collision between vehicle 1 and PTW 2 is prevented when PTW 2 informs vehicle 1 to stop its overtaking procedure. This situation is critical for PTW users due to blinds spots and differential of speed between PTW and a car which does not allow the driver to be aware of the presence of a motorcyclist. The purpose behind this use case is to avoid collision between PTW and vehicles by giving a warning to the vehicle.

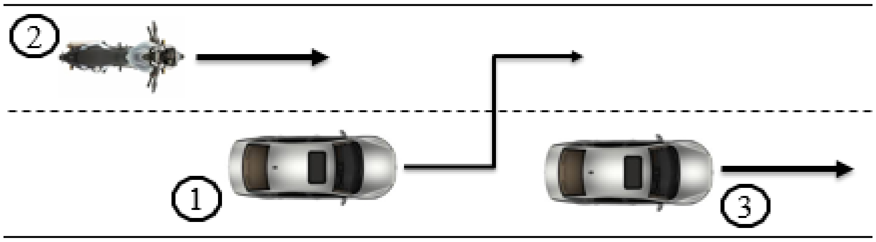


Figure 1.5. Safe overtaking in urban roads

- ✓ *Head on collision warning (Do Not Pass Warning)*

DNPW [137] [138] reduces the risk of a head collision by sending early warnings to vehicles that are traveling in opposite directions. This use case is also denoted as “Do Not Pass Warning”. As shown in Figure 1.6, vehicle 1 attempts to overtake vehicle 3 which obstructs the driver's 1 field of view, while vehicle 2 is approaching from the opposite lane. The purpose behind this use case is to warn the driver of vehicle 1, of an incoming vehicle in the adjacent lane. Thus, vehicle 1 needs to delay or abort the overtaking manoeuvre. This allows to avoid accidents linked to head on collision situations.

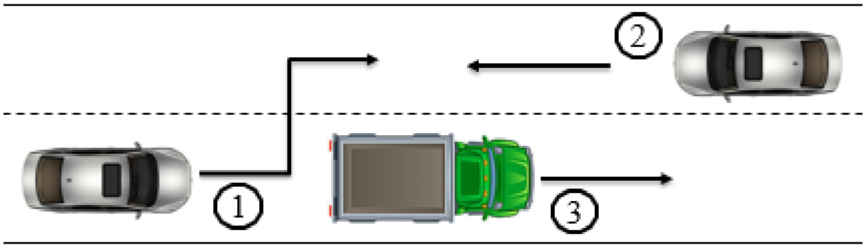


Figure 1.6. Head on collision warning

- ✓ *Intersection collision warning (ICW)*

ICW [137] [138] aims at reducing the risk of lateral collisions for vehicles that are approaching road intersections. The danger is detected by vehicles or RSUs. The information is signaled to the approaching vehicles in order to lessen the risk of lateral collisions. Figure 1.7 depicts an example of the Intersection Safety application.

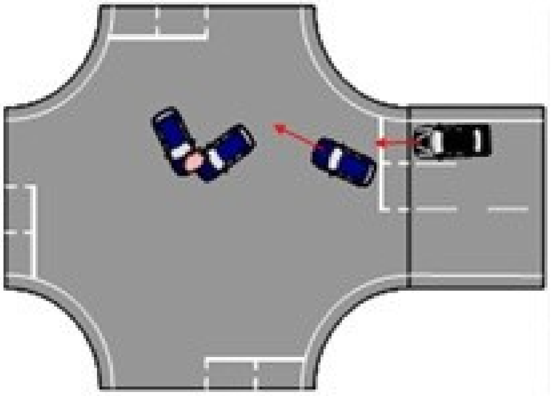


Figure 1.7. Intersection Collision Warning [138]

A crash happens at an intersection creating a dangerous situation. Now, drivers approaching this intersection will be warned about the crash. The purpose of this use case is to avoid critical situations resulting from an accident beforehand. Intersections are probably the most complex part of road infrastructures and places where collisions can result in serious injury or death. An accident at an intersection can result in other accidents as an unforeseen situation would exist. At intersections, traffic-flow is very complex. Hence, the driving behaviour of other drivers could change immediately, due to such unforeseen situations [138].

✓ *Post-Crash Notification (PCN)*

In PCN [137], a vehicle involved in an accident would broadcast warning messages about its position to trailing vehicles (in the risk zone) so that they can take decision with time in hand. The PCN application may be implemented using both V2V and V2I. V2V has the advantage of transmitting quickly the information through a discover-and-share policy. Using specific sensors, PCN consists of measuring possible changes in the rational behavior of the driver (e.g., quick brake use, rapid direction changes, and so on), which are then communicated back to other vehicles along the same direction (See Figure 1.8).

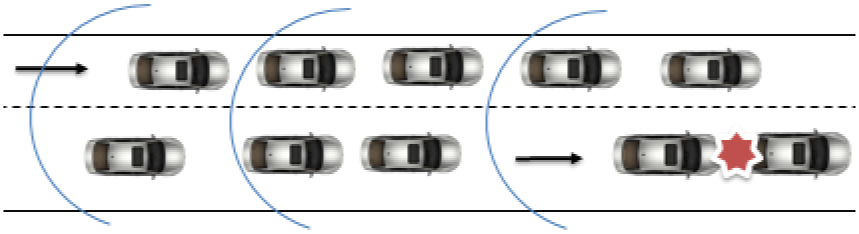


Figure 1.8. Post-crash notification

✓ *Cooperative Collision Warning (CCW)*

CCW [137] [138] is a wireless communication based collision warning. Especially, CCW is supposed to allow warning in the context of road geometry changes (i.e., road curves). CCW has advantages over In-vehicles sensor warning systems which are expensive, or even useless, in some situations (i.e., road curves). CCW provides warnings to drivers based on the motions of neighboring vehicles. Indeed, each vehicle, through GPS, is able to estimate its location relative to surrounding vehicles. Such an information enables to alert and warn drivers of impending threats (i.e., a stopped or slow-moving vehicle before arrival at the curve) without the use of sensors. A V2V cooperative safety system is, then, formed to forward collision warning. A typical CCW use case is depicted in Figure 1.9. Before arriving to the curve, vehicle 2 can detect a stopped car while driving (V1). This can be done by estimating the relative distance. Not so different from PCN, the information is flooded to the vehicles in the risk zone. Note that CCW is set up only in a V2V communication mode.

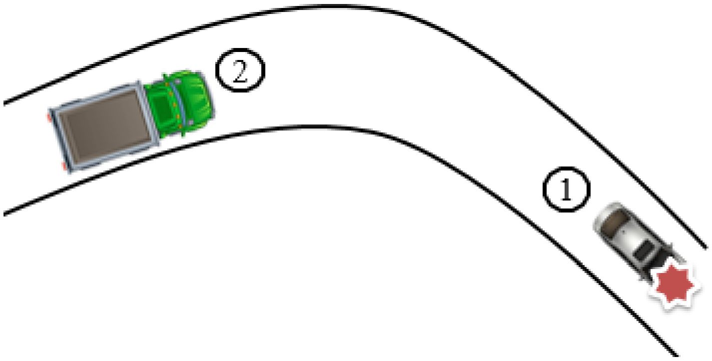


Figure 1.9. Cooperative collision warning due to a stopped vehicle

In situations where the maximum radio communication range does not reach the intended distance, message dissemination using multi-hop broadcast is necessary. This will be addressed in Chapters 3 and 4.

1.2.4.2. Traffic efficiency and management

Traffic efficiency and management applications focus on improving traffic flow. Speed Management (SM) applications [5] assist drivers in managing the speed of their vehicles to avoid unnecessary stopping. Cooperative Navigation (CN) applications [5] aim to manage the navigation among vehicles, like platooning. Congestion Road Notification (CRN) applications [5] detect and notify drivers about road congestions; CRN is used for route and trip planning. It evaluates new routes when heavy congestion is detected on a route or a portion of it.

1.2.4.3. Infotainment applications

The aim of infotainment applications is to offer comfort to drivers and/or passengers. In modern cities, people spend a considerable amount of time commuting by car from one place to another. A plethora of infotainment applications [6] are made available to vehicular users anytime and anywhere. This calls for vehicular networks to provide Internet access to vehicles. Infotainment applications include content download, media streaming, VoIP, social networking, gaming, cloud access, etc. Infotainment applications will be offered to passengers using service channels. A number of these applications is based on delay-sensitive video streaming requiring real-time transmission. To enhance the end-user experience, parameters such as frame rate, frame dropping, and timeliness are the basis of a good video quality. Hence, infotainment applications require low end-to-end delay and high reliability (low packet loss). More details about QoS support in infotainment applications can be found in [7] [8] [9].

- ✓ *Internet Access*

In-vehicle Internet access [10] allows a vehicle to connect to the Internet (e.g., to use infotainment applications) through an Internet gateway. Typically, a vehicle connects to an Internet gateway in its vicinity. In case no Internet gateway in the range, a vehicle relies on multi-hop communications to connect to an Internet gateway beyond its transmission range. An Internet gateway discovery protocol is, then, required to discover routes (i.e., an established route is a fixed succession of nodes between the source and the destination) to Internet gateways not in the range. Internet service providers (ISPs) offer Internet access through various wireless technologies (i.e., LTE) using Internet gateways. Once connected to Internet, a vehicle can access Internet services (i.e., email). In the following, we briefly describe Internet gateways as well as the gateway discovery/advertisement process.

- ✓ *Internet gateway*

Traditionally, an Internet gateway is an RSU, installed in fixed position along a roadside [36]. Unfortunately, Internet access through RSUs requires pervasive RSUs to ensure each vehicle is in RSU’s transmission range [11] (i.e., the typical range of an RSU is few hundred meters). Such a requirement incurs high infrastructure deployment cost. Several research efforts [12][13][14][15][16] are proposed to optimally place RSUs. Indeed, deploying a new RSU needs intensive investigation [11]; for instance, the land where to place a new RSU may be private requiring owner permission. It may be difficult, if not impossible, to get such a permission.

Therefore, deploying new RSUs often requires a large amount of investment and elaborate design, especially at the city scale. Consequently, Internet access systems that rely only on roadside infrastructure are impracticable to be implemented. Recently, the concept of long-term evolution (LTE)-connected vehicles [17] (i.e., a vehicle equipped with 802.11p and LTE interfaces) has received a lot of attention. Once in the range of a LTE base station, the vehicle gets Internet access. Actually, LTE provides a robust mechanism for mobility management of vehicles [18] (i.e., supports data rate of 10 Mbps with speed up to 140 km per hour). LTE also fits the bandwidth demands and the quality of service requirements of infotainment applications [18]. However, mobile data is experiencing explosive growth [19]; this makes LTE cellular infrastructure bandwidth not able to keep up with connecting high number of connected vehicles [20]. Also, it has been reported that cellular infrastructure connectivity cannot evolve once it is installed [17]. Furthermore, many vehicles incur frequent handoffs, because of high mobility, requiring higher bandwidth [21]. Hence, allowing only some connected vehicles to operate as Internet gateways (mobile Internet gateways) to other vehicles may be effective [22]. Various Internet access systems using connected vehicles as Internet gateways [23] [24] [25] [26] have been proposed. Getting Internet access through either RSUs ([12] [13] [14]) or connected vehicles ([23] [24] [25] [26]) relies on multi-hop communication links [36].

✓ *Gateway discovery/advertisement*

Gateway discovery/advertisement is the process of finding a gateway that matches the requirements of requestors (i.e., vehicles). Conventionally, an Internet gateway periodically advertises its services (i.e., broadcasts an advertisement message) to announce its presence in either one-hop or multi-hop area using flooding. Furthermore, a requester (vehicle), in turn, discovers and selects gateways using a gateway discovery scheme; the requestor sends discovery messages, in the network to establish a route to a convenient gateway. Route discovery process relies on multi-hop broadcasting to find an appropriate Internet gateway. Existing gateway discovery/advertisement schemes are reviewed in Chapter 2.

1.3. Motivations and Problem statement

V2V and V2I communications are expected to enable diverse safety and infotainment applications. IEEE DSRC/802.11p is the emerging communication standard for vehicular communication. Broadcast is the preferred communication mode for vehicular applications.

In big cities, several emergency events have to coexist together to achieve life-saving goals. On detecting an unexpected event (i.e., a traffic accident), a vehicle immediately issues an event-driven message to notify neighboring vehicles/drivers ahead of time to allow them to take action in time. Conceived to be just up to few hundred meters [27], an emergency message has to be forwarded hop-by-hop to far-away vehicles (in the risk zone). Figure 1.10 shows a scenario of hazardous driving conditions on adjacent road segments.

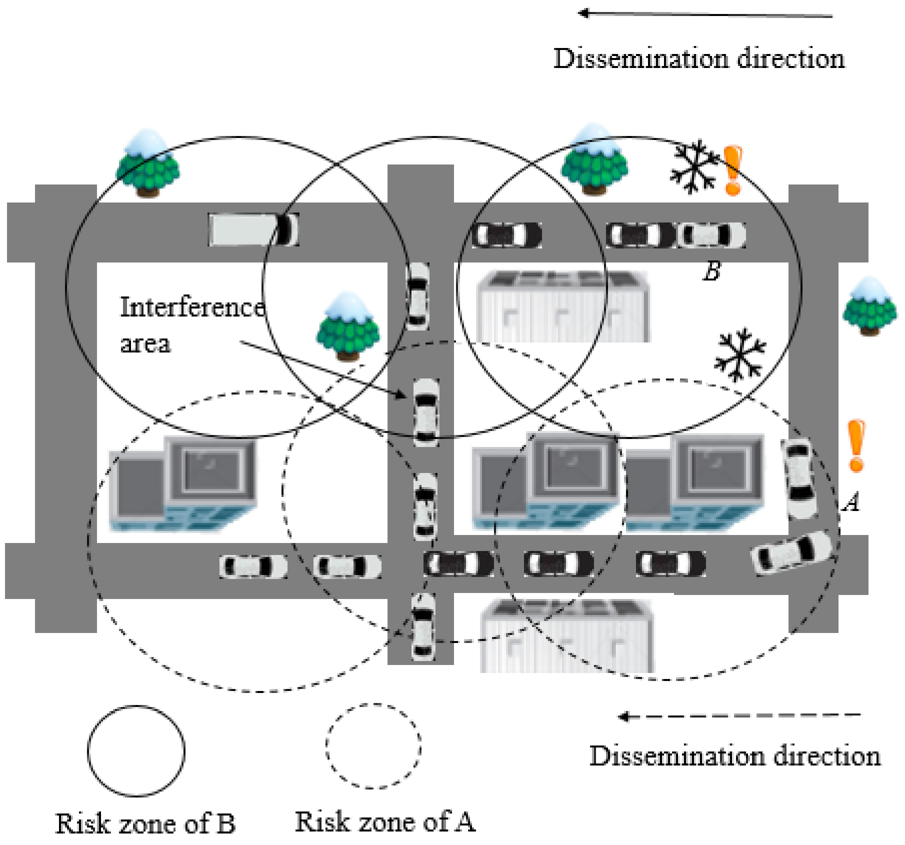


Figure 1.10. Illustration of multiuser interfering nodes

Vehicle A (involved in a crash) broadcasts an emergency message M_A to the vehicles in the risk zone of A. Vehicle B (involved in a crash) broadcasts an emergency message M_B to the vehicles in the risk zone of B. On receiving a message, a vehicle can slow down/brake to avoid hitting the car(s) it follows. A single uninformed vehicle, may result in terrible causalities [27][28][29][30]. The successful dissemination of emergency messages makes a difference between life and death. Thus, no driver should be deprived of information about emergency events. Broadcast-based emergency message dissemination needs timely and lossless medium access. Consequently, high reliability of message dissemination is required (e.g., the probability of packet reception should be greater than 0.99 [29]).

Infotainment applications call for vehicular communication networks to support Internet services in vehicles [31]. Indeed, In-vehicle Internet access [10] allows a vehicle to connect to the Internet through an Internet gateway. Traditionally, an Internet gateway is RSU, installed at fixed position along a roadside. Recently, the concept of LTE-connected vehicles [17] (i.e., a vehicle equipped with 802.11p and LTE interfaces) has received a lot of attention. Once in the range of a LTE base station, the vehicle gets Internet access. Allowing some connected vehicles to operate as Internet gateways (mobile Internet gateways) to other vehicles may be effective [22]. Getting Internet access through either RSUs ([12] [13] [14]) or connected vehicles ([23] [24] [25] [26]) relies on multi-hop communication links. Typically, a vehicle connects to a gateway in its vicinity. In case no Internet gateway in the range, a vehicle relies on multi-hop communications. To do so, an Internet gateway discovery scheme is required to discover routes (i.e., an established route is a fixed succession of nodes between the source and the destination) to Internet gateways not in the range. Internet gateway discovery schemes should be enable the establishment of reliable paths to Internet gateways. The discovery process can be done in two ways: (1) a gateway periodically sends advertisement messages; or (2) a requestor sends discovery messages. If some nodes along the path have low reception probability, the communication would be stopped.

Nevertheless, many factors can influence probability of successful message reception in wireless communications. In vehicular networks, vehicles share a common wireless channel by using the same radio frequencies. Each node competes for channel access when it needs to transmit, without any guarantee of success. Typically, several factors reduce probability of successful message reception in wireless communications. Random loss is caused by lossy wireless channels and node mobility. In city road networks, severity of interfering nodes increases (i.e., overhearing a packet not intended for the receiving node is considered as interference) [29] [30]. Vehicles may receive signals from other vehicles on adjacent streets. Both periodic messages (i.e., beacons) and emergency messages [30] are transmitted on CCH. Beacons increase the severity of interfered/collided packets. Furthermore, high mobility of vehicles makes reliability of communication in vehicular networks more complex [27].

Despite DSRC/802.11p based broadcast has the potential to provide low latency in one-hop [28], it is reported to be defective in terms of reliability making it a major reason that hinders the deployment of IEEE DSRC/802.11p [32]. IEEE DSRC/802.11p defines the MAC layer to be based on CSMA/CA [32] with minor modifications. The channel access mechanism of DSRC/80211p is Enhanced Distributed Channel Access (EDCA); it is not able to provide predictable reliability for safety services. As a result, IEEE DSRC/802.11p MAC is not able to guarantee broadcast reliability. More specifically, 802.11p MAC does not implement any broadcast reliability mechanism [33] (e.g., DSRC/802.11p-based broadcast does not support acknowledgement [32]). Comparing broadcast to unicast, no mechanism is used to alleviate the hidden terminal problem (i.e., virtual carrier sensing is not used in IEEE 802.11 broadcast [32]). Hence, the current draft of IEEE 802.11p MAC [34] [35] cannot meet strict reliability requirements (e.g., 99%).

In multi-hop broadcasting, the probability of successful message reception decreases with the number of hops [36]. Forwarder selection increases the probability of collisions/interference [28] [33]. IEEE 802.11 MAC does not offer any specific support to improve reliability in multi-hop, apart from the naïve flooding scheme [38]. However, such a solution may lead to the broadcast storm problem [39] resulting in unreliability (i.e., high packet loss) and delayed communication [39].

Thus, the objective of this dissertation is to contribute to the design and the evaluation of new solutions that ensure efficient safety message dissemination (multi-hop communications) for urban vehicular applications considering QoS requirements (i.e., delay and reliability). On one hand, this work proposes two new emergency message dissemination schemes that provide best reliability, compared to existing schemes, while satisfying delay requirements of safety applications. On the other hand, it proposes and evaluates, an Internet access scheme that provides Internet access to vehicles considering delay and reliability in order to enable infotainment applications.

The first 2 contributions of this thesis address the problem of emergency message dissemination, in urban VANETs, considering the requirements of safety applications in terms of reliability (packet reception rate) and delay. In the literature, several approaches have been proposed to deal with this issue. Among them, Several CSMA-based multi-hop broadcast schemes have been proposed (e.g., [60][33][26][61][42][43][44][45]). Despite their good performance in low density network, exiting schemes sustain major shortcomings in urban environment. On one hand, in fast schemes (e.g., [60][33][26][61][62]), the emergency message is forwarded to selected forwarders in quick successions. However, in case the forwarder has moved away or is malfunctioning, the multi-hop communication would not be possible. Efficient schemes [42][43][44][45], on the other hand, propose techniques to mitigate the broadcast storm problem. However, these schemes don't consider MAC layer issues in their forwarding node selection mechanism yielding to unreliable transmissions. They use control packet exchange and/or acknowledgement packet and select a single forwarding node at each hop. DSRC/802.11p-MAC [32] can't characterize/detect random access events resulting in unreliability. In harsh network conditions, a sender does not know whether its transmitted message is successfully received or not. Recently, repetition-based broadcast MAC schemes (e.g., [46][48]) have been proposed to enhance broadcast reliability for safety applications. The basic idea is to repeat (i.e., transmit) the message multiple times within a frame in order to increase reception probability; a frame consists of L time slots. Random repetitions schemes like SFR [46] and AFR [46] randomly select repetition slots. It has been proved that selecting *k* slots out of L raises the probability of successful message reception [46]. Expanding upon this finding, structured repetitions are proposed to further protect repeated packets from hidden terminal problem [49]. Positive Orthogonal Codes (POC), known as Uni-Polar orthogonal codes (UPOC) [47], as structured repetition patterns, have been reported to suppress hidden terminal problem [49]; an UPOC is a binary code of fixed length L, where cross-correlation between any pair of code-words is less than a given value [49]. However, without evaluating the channel condition, if fixed number of messages is forwarded within frame, we may be sending either too few or too many packets. Too many packets may lead to considerable overhead and too few packets may lead to unreliability. It is important to note that most existing Repetition-based MAC schemes [46][48][49] are not compatible with emerging DSRC/802.11p [32].

The third contribution focuses on the problem of providing Internet access in urban vehicular environments considering reliability and delay. Several Internet gateway discovery schemes (i.e., [50][26][51][52]) have been proposed in the literature. These schemes can be classified into three categories: (1) Proactive approaches: Internet gateways advertise themselves in the whole network; (2) Reactive approaches: vehicles that want Internet access, need to flood the network for Internet gateway discovery; and (3) Hybrid approaches: Internet gateways advertise themselves to their neighbors (1 or n hops away); then, requesters send packets to find an Internet gateway in these advertisement areas. Despite their good performance in 1-hop, existing schemes (e.g., [26][51][53][54]) make use of link stability metric, which is based only on mobility metrics (e.g.,relative motion between neighboring vehicles, speed, etc.), to determine paths to Internet gateways. In city settings, such a selected route can be broken frequently owing to the high mobility of vehicles. Any node that ensures progress toward the destination can be used for forwarding. The forwarding decision is based on the position of destination vehicle and position of one hop neighbors. However, the link to the selected node may be unreliable in harsh network conditions leading to packet loss. From above discussions, we can conclude that the route discovery schemes do not guarantee reliable communication, in city settings.

1.4. Thesis Contributions

The thesis consists of three contributions: (1) a reliable multi-hop broadcast scheme, called Reliable Emergency Message Dissemination scheme (REMD), suitable for a wide range of vehicular safety applications; (2) a new multi-hop broadcast scheme, called Bayesian networks and unipolar orthogonal Code based Reliable multi-hop Broadcast (BCRB); and (3) an Optimal Gateway Placement and Reliable Internet Access in Urban Vehicular Environments, called reliable multi-hop Internet access system (called RICS) for urban vehicular environments.

In the first contribution, we propose REMD which is compatible with IEEE DSRC/802.11p. Basically, REMD divides the target area into multiple cells (fine-grained vehicle positions) to form adjacent grid-like zones. REMD consists of 5 proposals (1) a curve-fitting and polynomial extrapolation based scheme to estimate, with good accuracy, the reception quality of link (in each cell) in the transmission range of the sender; (2) a Max-Min optimisation problem and its resolution that allows to determine an optimal number of repetitions (i.e., message transmissions) to satisfy 1-hop reliability requirements. The problem resolution consists of calculating packet reception rate (PRR) using exact Poisson's binomial distribution. In urban vehicular networks, Poisson's binomial distribution does not follow an asymptotic Poisson distribution. We turn to find the exact formula of probability mass function (p.m.f) of the distribution using a Fast Fourier transform (FFT) based algorithm, labeled PMF-FFT. The time complexity of PMF-FFT is $O(n \times \log(n))$, where n is number of cells. The input to the optimization problem is link reception qualities computed in (1); (3) a UPOC-based scheme that carefully generates repetition patterns to minimize/avoid interferences between senders (vehicles) located on different road segments; (4) a scheme that selects appropriate forwarders, at each hop, with the objective to satisfy multi-hop reliability requirements. These forwarders, at each hop, cooperatively repeat the message (based on the number of repetitions computed in (2) and repetition patterns determined in (3)) to support reliability requirement in next hop; and (5) a sub-layer between MAC and LLC responsible for generating broadcast repetitions. Simulations validated REMD (the analytical model) and did show its outperformance compared to existing schemes in terms of reliability, end-to-end delay and network load.

In the second contribution, we propose BCRB which is compatible with IEEE DSRC/802.11p; it focuses on the main limitations of the first contribution: (1) link reception quality estimation: BCRB proposes a Bayesian networks based scheme to estimate, with good accuracy, link reception quality, at different locations in the zone covered by the transmission range of the sender. This estimation is based on executing a training data collection phase (TDC) that exploits beacons periodically generated by vehicles. To learn the Bayesian network, we make use of a modified version of PC [111] algorithm, called V-PC, together with the Expectation Maximization (EM) [116] algorithm. We make use of a graph indexing method to execute V-PC in $O(n)$, where n is number of cells; and (2) Optimal number of repetitions: BCRB proposes a more accurate resolution of the Max-Min optimisation problem that allows determining an optimal number of repetitions (i.e., message transmissions) to satisfy 1-hop reliability requirements for each receiver in transmission range. More specifically, BCRB guarantees broadcast reliability for each receiver in the zone covered by the transmission range of the sender using a combination of packet delivery probability (PDP) and packet reception rate (PRR) metrics. Simulations validated our scheme (the analytical model) and did show its outperformance compared to existing schemes in terms of reliability, end-to-end delay and network load. Furthermore, simulations did show that both REMD and BCRB successfully provide assured reliability while satisfying end-to-end delay requirements of safety applications. BCRB could achieve less end-to-end delay and network load compared to REMD for all vehicle densities. Also, BCRB outperforms REMD in terms of link reception quality estimation accuracy especially in low vehicle density.

In the third contribution, we propose RICS for urban vehicular environments that uses our proposed BCRB. We make use of both LTE-connected vehicles and the already deployed RSUs infrastructure as Internet gateways. Indeed, RSUs have a considerable impact on network reliability, as they are fixed reliable nodes [55]. Because of random mobility of vehicles, there is the possibility of network fragmentation. Static RSUs may act as bridges between fragmented groups of vehicles [11]. LTE-connected vehicles enhance Internet gateways availability because adding such vehicles (e.g., buses and taxis) doesn't require additional infrastructure (e.g., land). In [22], it has been reported that using connected vehicles as Internet gateways increases the probability, for moving vehicles, to set up paths with fewer hops. To ensure reliable multi-hop In-vehicle Internet access, we determine minimum possible communication hops, from a requesting vehicle to a fixed/mobile Internet gateway, with high reliable advertisement message dissemination. To accomplish this, we model the Internet gateways placement problem (called GP) as a 2-dimentional k-center [56] optimization problem. This problem is known to be NP-hard. We make a dimension reduction of the optimization problem and propose an exact time resolution algorithm $O(n^2 \times \log(n))$, where n is number of vehicles, to solve it. In addition to computing minimum communication hops, we implement an Internet gateway discovery protocol (using BCRB) which exploits the reception quality of 802.11p wireless links to establish high reliable communication paths. Simulations did show that RICS outperforms existing schemes in terms of reliability, end-to-end delay and network load.

1.5. Thesis Organization

The rest of this thesis is structured as follows. In Chapter 2, we describe existing approaches in the literature that address the aforementioned issues (i.e., emergency message dissemination and Internet gateway discovery/advertisement process in vehicular network). Chapter 3 presents REMD. Chapter 4 describes BCRB. Chapter 5 presents RICS. Chapter 6 summarizes the major contributions of this dissertation and outlines few/possible future research directions.

Chapter 2
Related work

2.1. Introduction

IEEE DSRC/802.11p based broadcast is the preferred communication mode for vehicular applications. Several safety applications forward emergency messages hop-by-hop to vehicles in the risk zone. Infotainment applications call for vehicular networks to support Internet services in vehicles [31]. An Internet gateway discovery scheme is required to establish multi-hop communication path to an Internet gateway. Both safety and infotainment applications have rigid QoS requirements (i.e., delay, reliability). Flooding seems to be the straightforward technique for multi-hop broadcasting in vehicular networks. However, it is not used since it will cause a sharp drop in the performance of vehicular applications. Non-flooding methods are, then, preferred. Yet, several challenges face these methods in urban vehicular networks.

The remainder of the chapter is organized as follows: Section 2.2 describes challenges of flooding. Section 2.3 briefly describes broadcasting challenges in urban settings. Section 2.4 reviews emergency message dissemination schemes that are proposed in the literature to ensure reliability and delay requirements for safety applications. Section 2.5 reviews Internet gateway discovery/advertisement approaches that are proposed in the literature to ensure access of vehicles to Internet. Section 2.6 concludes the chapter.

2.2. Flooding

Flooding, also called blind flooding, is the simplest solution to reach all nodes in vehicular networks. It is the straightforward solution to perform multi-hop broadcasting. The main idea is that when a vehicle receives a message, it checks whether it is the first reception of this message. If the response is yes, it rebroadcasts it; otherwise, it discards it. Flooding has several drawbacks:

✓ *Redundancy*: A vehicle may broadcast a message to its neighbors while all the neighbors might already have received the message. The main reason for redundancy is that transmission ranges of vehicles may overlap with each other. Redundancy is also related to network density; indeed, a node may receive as many messages as it has neighbors in its transmission range. In vehicular networks, a node may have up to 100 neighbors (i.e., transmission range of the IEEE DSRC/802.11p may reach up to 1 km and the density of vehicles may reach more than 100 vehicles per kilometer) [57]; in this case, flooding results in 100 receptions by vehicle.

✓ *Collisions*: VANET is a CSMA/CA vehicular network. This means that each vehicle is equipped with a CSMA/CA transceiver that accesses the air medium following IEEE DSRC/802.11p. Here, collisions occur for 3 major reasons: (a) Vehicles use the back-off mechanism of DCF which is defective in dense network. This is because neighboring vehicles may have passed their back-off procedures and after hearing the broadcast message (and having passed a DIFS period), all neighbors may start rebroadcasting at around the same time; (b) The RTS/CTS control packet handshake is not used in a broadcast transmission. The number of collisions caused by the hidden terminal problem may be significant; and (c) A collision detection (CD) is absent in IEEE 802.11p. Once a collision occurs, without collision detection (CD), a vehicle keeps transmitting the message even if its previous messages are lost, which leads to further collisions.

This phenomena, caused by flooding, is called "broadcast storm" problem which results in unreliability (i.e., high packet loss) and high latency [39]. Non-flooding techniques which allow only a subset of vehicles to rebroadcast the message, are, thus, preferred. Non-flooding is based on selecting a subset of neighboring vehicles, called "*forwarders*", which rebroadcast the received message to next hop vehicles. Originating from the source node, a message is broadcasted through the forwarders in order to reach vehicles in target area (e.g., risk zone). Non-flooding techniques carefully select forwarders in order to satisfy application requirements in terms of reliability and delay. Indeed, the objective of these methods is to compensate the lack of reliability in IEEE DSRC/802.11p and/or guarantee rapid delivery of messages.

2.3. Broadcasting challenges in urban environment

Broadcasting faces several challenges in city setting. Especially, transmission in wireless medium is vulnerable to packet collisions and interferences due to various wave propagation issues (e.g., signal attenuation, noise and jitter). Indeed, a transmitted signal undergoes three principal physical phenomena (i.e., diffraction. refraction and scattering) in the presence of obstacles, e.g., buildings. These are quite predominant in urban vehicular networks in the presence of high rise buildings and moving vehicles (e.g.,big trucks) making vehicular communication quite unreliable. Furthermore, transmissions originated from vehicles on neighboring streets (e.g.,parallel/perpendicular streets) interfere with each other resulting in collisions. Achieving very high reliability in the presence of all kinds of wireless network vulnerabilities is a major challenge in vehicular networks. Several non-flooding techniques have been proposed for emergency message dissemination and/or gateway discovery. In the following sections, we review the most representative approaches.

2.4. Emergency message dissemination

Emergency messages are designed for life-saving goals. Hence, emergency message dissemination needs timely and lossless medium access. The first part of this section presents the different CSMA-based broadcast medium access control (MAC) schemes that have been designed for multi-hop broadcasting together with their limitations. The second part of this section presents repetition-based broadcast medium access control (MAC) schemes together with their limitations. Afterwards, we outline our proposed solutions to ensure reliable and rapid emergency message dissemination in urban environment.

2.4.1. CSMA-based multi-hop broadcast

IEEE DSRC/802.11p CSMA/CA-based MAC does not offer any specific mechanism to disseminate data considering applications requirements (reliability and delay) in multi-hop, apart from the naïve flooding scheme [38]. To avoid the broadcast storm, different CSMA-based multi-hop broadcasting schemes have been proposed in the literature. They can be classified into three broad categories: Probabilistic schemes (i.e., [37][58]), Backbone-based schemes (e.g., [59] [44]) and Delay-based schemes (e.g., [60][33][26][61][62][63][64]).

2.4.1.1. Probabilistic schemes

Probabilistic schemes are designed to alleviate broadcast storm problem. These schemes propose selecting forwarders by the use of probabilistic broadcasting, also called probabilistic flooding. The main idea is to reduce the percentage of redundant messages by selecting only some vehicles to rebroadcast messages. Wisitpongphan et al. [58] proposed weighted p-persistence, slotted 1-persistence, and slotted p-persistence schemes. The three broadcast techniques are the first attempt to mitigate broadcast storm problem in vehicular networks. Each vehicle calculates its own broadcasting probability based only on a local information. Upon receiving a packet from a neighboring node i, node j checks the packet ID and rebroadcasts with probability p_{ij} if it receives the packet for the first time; otherwise, it discards the packet. In p-persistence, p_{ij} denotes the ratio of the relative distance between nodes i and j to the average transmission range of the nodes. In 1-persistence, each vehicle is assigned a broadcast probability set to 1 at an assigned time slot t_{ij}. Recently, Mylonas et al. [37] proposed SAPF, which is designed for emergency message dissemination. SAPF determines broadcast probability adaptively based on the speed of vehicles. The reasoning behind this is that low vehicle speeds in freeway setting imply high vehicle density; this, in turn, implies that high reliability can be achieved by choosing relatively low rebroadcast probability values. However, in urban setting, probabilistic broadcasting schemes face serious challenges. These schemes do not consider wireless signal propagation issues (e.g., severe multi-path fading and shadowing); in high lossy channels, they generate redundant retransmissions and incur large communication delays. This makes them not suitable for safe driving in dense urban areas. Furthermore, these schemes do not consider MAC layer issues, such as interference management and random access which make them not good candidate for applications in vehicular networks.

2.4.1.2. Backbone-based schemes

Backbone-based schemes (e.g., [59][44][65]) are designed to alleviate broadcast storm problem using already established virtual multi-hop backbone structures. The idea of establishing a virtual backbone structure is brought from wired networks. The objective backbone-based schemes is to establish a virtual backbone network using best interconnected nodes. In a backbone structure (see Figure 2.1), a subset of all vehicles has to be selected to form the backbone. These vehicles are, thus, the forwarders. DBA-MAC [44] is designed for the highway scenario. It selects backbone nodes (i.e., a chain of forwarders) based on estimated lifetime of wireless links. The link lifetime between a pair of vehicles is the time duration that the two vehicles can communicate with each other without any breakage/termination. In city setting, surrounding buildings and mobility of nodes impact quality of wireless links resulting in weak connectivity between backbone nodes. Ros et al. [59] proposed ABSM which selects backbone nodes using connected dominating sets (CDS); it uses neighbors' elimination to select backbone nodes [65]. A neighbor elimination scheme prevents a node from retransmitting if all its neighbors already received the same message. In ABSM, links of the backbone nodes may have low quality resulting in high communication overhead while trying to maintain the backbone (e.g., because link failure).

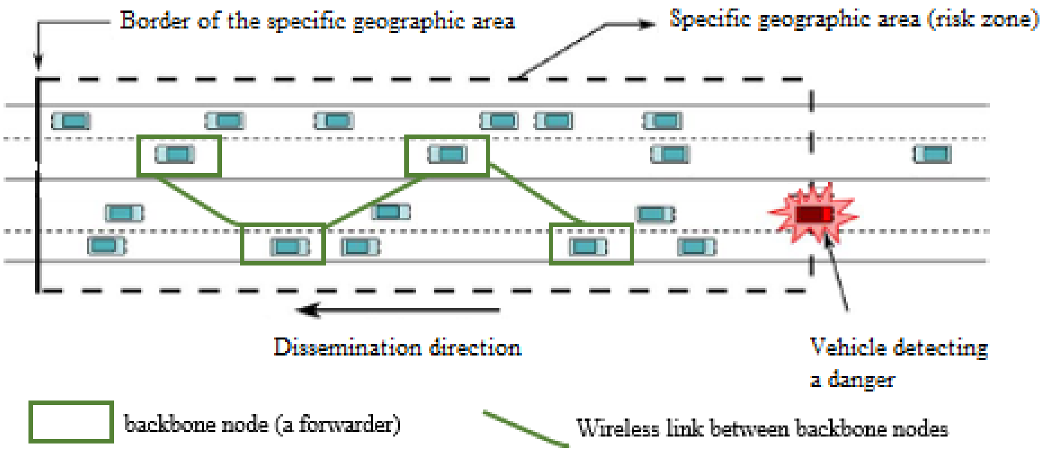


Figure 2.1. Illustration of a backbone in vehicular networks

Recently, togou et al. [65] proposed SCRB which is a CDS-based data forwarding protocol for urban vehicular environment that builds backbones on road segments and connects them at intersections via bridge nodes. These nodes assign weights to road segments based on the collected information of delay and connectivity. Routes with the lowest aggregated weights are selected to forward data packets. However, collected information is based on estimated link lifetime between backbone vehicles in order to predict the time to elapse before a disconnection occurs. In lossy channel, links of the backbone nodes may have low reception quality resulting in frequent links failures.

Intermediate nodes are the vehicles located in the area between two successive backbone nodes. To enhance broadcast reliability, ABSM includes message identifier in beacons to serve as acknowledgements. If an acknowledgement is not received from an intermediate node, the backbone node rebroadcasts the message. In urban environment, the presence of obstacles may cause massive beacon losses. In this context, ABSM [59] performs redundant retransmissions. At the other extreme, the backbone nodes that are responsible for message dissemination at each hop may not be in farthest positions resulting in high number of communication hops. In this case, both DBA-MAC and ABSM may achieve high communication delay (multi-hop time delay of data transmission increases with communication hops) making them not suitable for safety applications. Furthermore, over time, the backbone structure in DBA-MAC and ABSM must change to match the changes in the network topology as vehicles move around (e.g., turn right/left); this may result in high network overload (creation and maintenance of backbone structure) degrading the network performance.

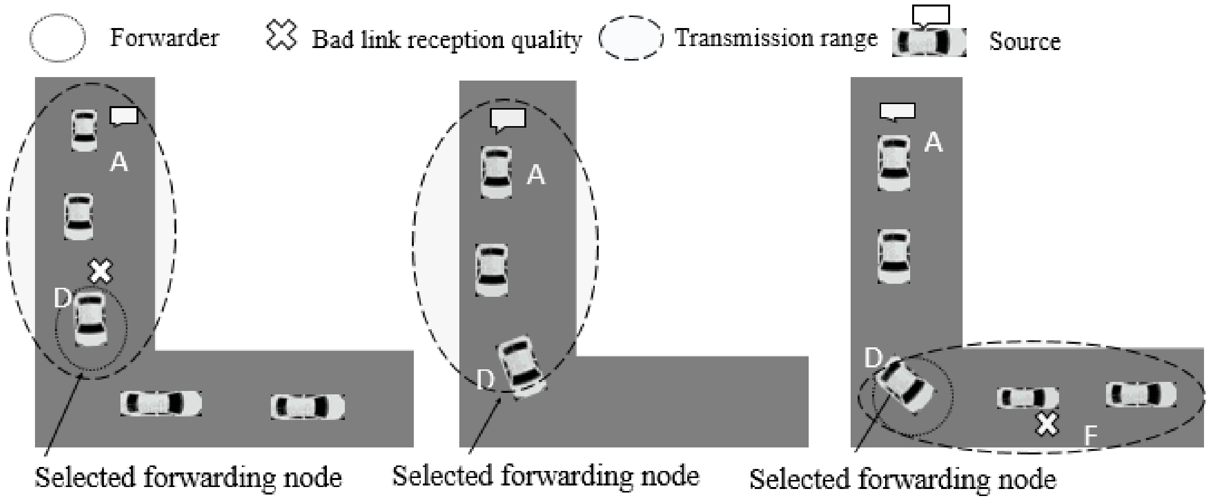
2.4.1.3. Delay-based schemes

In the case of DSRC-based safety applications, stringent delay requirements need to be satisfied. To achieve lower delay, the node farthest from the source is generally selected to be the forwarder. Several methods have been proposed to select the farthest vehicle as the next relaying node (i.e., forwarder) in order to reduce hop count. Delay-based schemes (e.g., [64] [60][61][62][63]) are designed to focus on fast data dissemination. UMB [60] divides the transmission range into several sectors. The functions of forwarding and acknowledging the message are assigned to only one vehicle located in the farthest non-empty sector. 3P3B [63] iteratively partitions the communication range into small sectors. The partitioning mechanism allows the farthest possible vehicle in the farthest sector from the sender node to perform forwarding in order to increase the dissemination speed by reducing the number of forwarding hops. In order to give emergency messages a higher access priority to the communication channel, 3P3B makes use of a mini distributed inter-frame space (DIFS) in medium access control (MAC) sublayer In addition, it uses the RTB/CTB mechanism, which is similar to the request-to-send/clear-to-send mechanism in the IEEE 802.11 standard, in the partitioning phase to cope with the hidden terminal problem in multi-hop wireless networks. Messages, involved in collisions, are retransmitted to improve reliability (i.e., packet reception rate). Sharifi et al. proposed DPS [66] which computes the size of sectors (and thus the number) such that on average each sector contains at least one vehicle. In the back area of the sender, the probability that a single vehicle exists in each partition is equal or greater than a predefined threshold. In PAB [34], each node receiving a packet determines the distance with respect to the sender. Then, it picks a waiting time inversely proportional to the distance from the sender to the receiver. The farthest node is whose timer expires first. PMBP [61] and ROFF [62] select the farthest forwarding node according to its distance to the sender. In the above schemes (e.g., [60][34][61][62]), the sender is aware of the topology change through received beacons. The time gap between beacon sending time of a neighboring node and the time at which that node becomes a forwarder may be very long. In this case, the farthest node may not be within the range of the sender resulting in unreliability. Besides, one-hop broadcast reception rate is lower in farthest positions due to channel fading. As a result, the farthest node may not receive the message and the sender will remain unaware of failed reception. To overcome such limitations, several contributions (e.g., [60][62][63]) propose to use a handshake mechanism with the goal to decrease the impact of hidden terminal problem and/or to transmit acknowledgements (ACKs). To combat hidden terminal problem, schemes in [60][67] use request-to-send/clear-to-send (RTS/CTS) mechanism before transmitting a data packet. UMB [60] uses RTS/CTS handshake with only one of the recipients among sender's neighbors. CLBP [67] exchanges BRTS/BCTS packets (Broadcast RTS/CTS inspired by the RTS/CTS mechanism in IEEE802.11) before sending data packet. BPAP [33] relies on control message exchanges similar to RTS/CTS handshake to overcome the hidden terminal problem. 3P3B [63] adopts RTB/CTB handshake to cope with the hidden terminal problem in multi-hop wireless networks. In city settings, control packets may be potentially lost because the length of safety messages is short and comparable to that of RTS control packets [64]. Therefore, the probability of collision for RTS packets is not negligible. Even if RTS/CTS handshake protects transmission of emergency messages when multiple interfering nodes coexist, it cannot protect from shadow and fading effects due to obstacles. Oppcast [68] and EMDOR [69] use explicit broadcast acknowledgements (ACKs) to select forwarders. However, acknowledgement-based mechanisms are generally not robust under harsh channel conditions. More specifically, ACK messages are prone to interference. In DPS [66], a handshaking mechanism that uses busy tones (instead of CTB) and RTB is used to let receivers know about the upcoming broadcast. The receivers, in response, transmit a busy tone to inform the hidden nodes about the upcoming broadcast. However, using busy tones signals would not be very effective in vehicular networks because a receiver cannot distinguish between two signals generated simultaneously from adjacent streets. In city settings, delay-based schemes (e.g., [60][64][63][61][62]) perform multiple retransmissions that may lead to the non-respect of delay requirements for safety applications.

Intermediate nodes represent the vehicles located in the area between two successive forwarders. With respect to the reachability of intermediate nodes, few delay-based schemes propose methods to ensure successful packet reception for intermediate nodes: (a) Schemes in [60][63][67] perform message “overhearing”; if farthest node is successfully selected, then the other nodes in between (i.e., intermediate nodes) can overhear the source transmissions [70]. In lossy channel, transmissions are vulnerable to interference/collisions. In this case, an intermediate node may not receive the message; (b) Scheme in [69] performs ACK-overhearing. After retransmitting, the forwarder sends an ACK to the sender. If an intermediate node overhears an ACK but it did not receive the corresponding message, it requests the sender to perform rebroadcasting. In the case of multiple nodes not receiving the message, the sender has to do multiple retransmissions that may lead to low packet reception rate (e.g., because of collisions). Hence, ‘’Overhearing’’ does not guarantee successful message reception; and (c) Oppcast [68] selects intermediate forwarders called “makeups” at each hop to enhance one-hop reliability; makeups are not responsible for forwarding the message to next hop. Indeed, their role is to perform rebroadcasting to enhance packet reception rate (PRR) at each hop. However, the makeups are selected, based on their distance to the sender. In adverse network settings, selected makeups may have low link reception quality resulting in non-guaranteed reliability for intermediate nodes.

2.4.2. Limitations of CSMA-based multi-hop broadcast schemes

Existing multi-hop broadcast schemes (e.g., [60][64][63][61][62]) are exposed to the following problems: (1) one forwarding node is selected per hop; and/or (2) unreachability of intermediate nodes problem. In Figure 2.2(a), source *A* selects farthest node *D*. Node *A* makes use of ACK and its associated timer-based rebroadcasting to select node *D*. In lossy wireless channel, ACK is vulnerable to packet loss. Furthermore, the number of retransmissions is almost unknown. To protect data packet, source *A* may make use of RTB/CTB; however, a single CTB may, in turn also, be vulnerable to packet loss in lossy wireless channel. Figure 2.2(b) shows that selected forwarding node *D* may be out of the transmission range or malfunctioning when data packet transmission occurs. Thus, the dissemination process can be stopped. Figure 2.2(c) shows that intermediate node *F* may have low link reception quality and does not properly decode the data packet. The sender *D* cannot detect such a failed reception. For CSMA-based MAC (i.e., [38] [33] [32] [37] [48] [49]), the successful reception of a packet by farthest neighbor does not guarantee successful reception by all neighbors.



(a) (b) (c)

Figure 2.2. Problems experienced by most of multi-hop broadcasting schemes: (a) – (b) Single forwarder problem, (c) Intermediate nodes reachability problem [106].

To conclude, conventional DSRC/802.11p-based MAC broadcast schemes are defective in terms of reliability. Motivated by these issues, a family of repetition-based broadcast MACs have been proposed for reliable transmission of short safety messages in VANETs [46].

2.4.3. Repetition-based Broadcast schemes

The objective of repetition-based MAC [46] is to meet one-hop requirements in terms of reliability and latency [46] in vehicular networks. The basic idea of repetition-based MAC is to divide time into frames of fixed size. A frame of L slots (equal to the message lifetime) is allocated to each vehicle intending to transmit an emergency message. Slot length assumes the transmission time of a single packet. A vehicle is allowed to repeat (i.e., transmit) the message multiple times within a frame. The intuition is that repeating the message more than once increases the probability of reception. Timeslots in which a node is allowed to transmit in a frame represent a repetition pattern. Repetition-based broadcast schemes can be divided into two broad categories: (a) Random repetitions; and (b) Structured repetitions.

2.4.3.1. Random repetitions-based schemes

Random repetitions [46][48][71] schemes randomly choose the repetition pattern (timeslots in which a node is allowed to transmit in a frame). SPR [46] transmits the message in each timeslot with probability p and remains idle with probability $1-p$. In this approach, a packet may be transmitted L times or not transmitted at all. SFR [46] randomly chooses k slots out of the L slots. It is proved in [46] that SFR is better than SPR and IEEE 802.11a in terms of reliability. FR-EMD [71] extends SFR to multi-hop and adjusts the number of repetitions according to vehicles density. However, it does not take into account signal propagation issues (i.e., slow-fading and shadowing) caused by obstacles. RB-CD [48] focuses on reliable broadcasting for emergency messages. The computation of the number of repetitions does not consider channel conditions. Furthermore, RB-CD [48] does not combat hidden terminal problem. In situations where a large number of transmissions happen, random access results in high packet loss rate. This is because randomly choosing transmission slots incurs collisions/interference.

2.4.3.2. Structured repetitions-based schemes

Structured repetitions [72][73][49] obtain the transmission slots based on orthogonal codes. It is shown in [72] that transmission/repetition patterns obtained from orthogonal codes [47] perform better than SPR [46] and SFR [46] in terms of probability of transmission success and delay. Unipolar orthogonal codes [47] represent binary sequences $\{0,1\}$, of length L, with small cross-correlation λ, where $\lambda \in \{0,1,2,\ldots,L\}$. Obtaining repetition patterns from these codes guarantees that maximum number of times that two vehicles simultaneously transmit is smaller than the cross-correlation threshold. Schemes in [72] [73] focus on broadcast reliability of periodic beacon messages using Unipolar Orthogonal Codes. The scheme in [72] does not account for fast moving vehicles and highly dynamic wireless channel. In POC-MAC [73], the distribution of repetition patterns, to vehicles, uses considerable channel resources (i.e., available codes are acquired through message-passing) in high density network. In lossy channel, the exchanged messages (message-passing between vehicles to update codes availability information) can be lost. This may cause erroneous code assignment (i.e., two neighboring nodes may allocate same code) resulting in unreliability. Furthermore, the authors [73] compute the probability of reception success without taking into account the specific characteristics of V2V communication, mainly signal propagation issues (e.g., multi-user interference and fading). This may result in non-realistic reception probability estimation results (i.e., either overestimating or underestimating success reception probability at different locations in the transmission range). In addition, repetition-based MAC schemes [72][73] are not compatible with emerging DSRC/802.11p [32]. CPF [49] extends POC-MAC [73] for multi-hop emergency message dissemination in highway scenarios. In lossy wireless channel, selected forwarders may have bad link reception quality resulting in failed receptions; whatever the number of repetitions, if a forwarder position is exposed to shadowing and multipath effects, the message dissemination may fail resulting in unreliability. All of these schemes (e.g., [72][73][49]) use fixed number of repetitions. Hence, they don't guarantee high broadcast reliability in lossy channel. Indeed, if fixed number of message repetitions is forwarded over a frame, they may be sending either too few or too many packets. Too many packets lead to message overhead resulting in collisions and too few packets lead to unreliability. Hence, an optimal number of repetitions must be determined according to channel conditions.

2.4.4. Limitations of repetition-based MAC schemes

Structured repetition-based schemes are proposed to further enhance probability of successful message reception, compared to random repetition schemes. Structured repetition-based schemes make use of Uni-polar orthogonal codes (UPOC) to time-separate senders in a frame. Despite their adequate performance in highway scenario, existing UPOC-based repetition schemes have three major limitations in urban scenarios: (a) relying on a fixed small number of repetitions cannot guarantee high reliability in time varying channel conditions (e.g., cannot be adapted to the worst channel conditions). On the other hand, excessive repetitions might cause network congestion; (b) they are not compatible with emerging IEEE DSRC/80.11p communication standard (CSMA MAC); and (c) They use codes assignment mechanisms that rely on messages passing between vehicles. In dense networks, these messages may be lost causing erroneous codes assignment.

2.4.5. Summary of emergency message dissemination schemes

Existing CSMA-based multi-hop broadcasting have a series of reliability drawbacks in urban environments (see Table 2.1). Forwarder selection and reachability of intermediate nodes are major issues. Structured repetitions-based MAC schemes are based on time division of transmitters in a frame. Yet, they have a number of limitations (see Table 2.1): (a) incompatibility with CSMA/CA of DSRC/802.11p and (b) inability to ensure QoS in time varying channel conditions.

Table 2.1. A comparison of emergency message dissemination schemes

Scheme	Forwarders selection			Interm. nodes reachability		MAC scheme	
						CSMA/CA	
	Farthest	RTS/CTS	ACK	overhearing	Fixed repetitions	yes	no
[60]	Y	Y	Y	Y		Y	
[64]	Y		Y	Y		Y	
[63]	Y		Y	Y		Y	
[61]		Y	Y	Y		Y	
[62]						Y	
[68]	Y		Y	Y			
[72]							Y
[73]					Y		Y
[49]					Y		Y

These observations have motivated us to propose two multi-hop broadcast schemes, REMD (see Chapter 3) and BCRB (see Chapter 4), compatible with DSRC/802.11p MAC. The proposed schemes provide solutions to existing reliability issues by introducing a proper design of emergency message repetitions and a multi-hop dissemination strategy. The main focus of REMD and BCRB lies in achieving very high reliability in multi-hop dissemination while keeping low end-to-end latency (comparable to delay-based schemes [38][64]) and low redundant message forwarding in lossy wireless channel. Basically, REMD divides the target area into multiple cells (fine-grained vehicle localization) to form adjacent grid-like zones and runs a proactive network state collection in each zone. REMD allows estimating, with high accuracy, the reception quality of links in the transmission range. Then, it uses this information in order to guarantee:

(1) One hop reliability of 802.11p-based broadcast:

- By carrying out an optimal number of emergency message repetitions. Repetition patterns are computed based on Uni-polar orthogonal codes (UPOC) to combat hidden terminal problem. A sub-layer between MAC and LLC is responsible on generating broadcast repetitions.

(2) Multi-hop reliability:

- By carefully selecting multiple forwarders and their positions, each single hop and
- By employing a cooperative communication scheme that allows forwarders to transmit the emergency message an optimal number of times with the objective to ensure high reliability.

BCRB was proposed to improve the performance of REMD. The key contributions of BCRB can be summarized as follows:

(1) Propose a training data collection phase that exploits periodic exchanged beacons to collect packet collision information at each possible vehicle location.

(2) Propose a Bayesian networks based scheme to estimate, with good accuracy, link reception quality, at different locations in the zone covered by the transmission range of the sender; this estimation is based on beacons periodically generated by vehicles.

(3) Determine an optimal number of repetitions (i.e., message transmission) to satisfy reliability requirements for each receiver in the area covered by the radio range of the sender.

2.5. Internet Gateway Discovery

Reliability is an important requirement for an Internet access system. Gateway discovery schemes use IEEE 802.11p multi-hop broadcast communication to establish paths to gateways (discover available gateways and select one). Several gateway discovery schemes (i.e., [50][26][51][52]) have been proposed in the literature. These schemes can be classified into three categories: (a) Proactive approaches; (b) Reactive approaches; and (c) Hybrid approaches.

2.5.1. Proactive approaches

In proactive approaches (e.g., [50][52]), gateways advertise themselves in the whole network by periodically broadcasting advertisement messages. If a vehicle receives more than one advertisement from gateways, it selects a best gateway. Criteria for selecting best gateway include end-to-end delay and estimated connection lifetime between the vehicle and gateway. Bechler et al. [50] proposed DRIVE where gateways use flooding to broadcast advertisement messages. The gateway with the maximum route connection’s duration is selected (duration represents the time elapsed before a connection breaks along the route; it is estimated using traffic density and distance to gateway [50]). Flooding results in redundant transmissions of advertisement messages which can cause high control overhead. To reduce this overhead and to cope with the high mobility of vehicles, Ngo et al. [52] proposed GD-ModCDS which uses virtual backbone construction based on Connected Dominating Set (CDS). In GD-ModCDS, gateways employ the concept of connected dominating set (CDS) to broadcast the advertisement message. Every vehicle is either in CDS or adjacent to at least one node in CDS. If only vehicles in the CDS retransmit the advertisement message once, all vehicles in the network can receive the advertisement message. The CDS nodes are selected using route lifetime parameter. The route lifetime is the minimum of the lifetimes of its constituent links; link lifetime is the time difference between link initiation and link breakage/termination. Link lifetime is determined as a function of speeds and moving directions of neighboring vehicles. In lossy wireless channel, selected CDS nodes may have bad link reception quality resulting in failed receptions; whatever the link lifetime of the constituent links, if a CDS node position is exposed to shadowing and multipath effects, the route with the best route lifetime to the selected gateway may be unreliable leading to packet loss. The gateway advertisement may fail resulting in unreliability. As gateways advertise messages in the whole network, selected gateway (having maximum link lifetime) may not the closest one resulting in higher communication hops. In [22], it has been proved that the number of breakages of a path increases with the number of hops in the path.

2.5.2. Reactive approaches

In reactive approaches (e.g., [26][51][53]), gateway discovery is initiated by vehicles. Indeed, vehicles (called requesters), that want Internet access, need to send solicitation messages in the network for gateway discovery to request Internet connection. Namboodiri et al. [26] proposed PBR for highway scenario. PBR exploits the predictable motion of vehicles on highways using location and speed of vehicles. This information can be exploited to predict how long a route will last between a vehicle requiring Internet connectivity and the gateway. Accurate prediction of route lifetimes can significantly reduce the number of route failures. Amadou et al. [51][74] proposed BCRPV to establish routes to gateways. The discovery protocol selects few forwarding nodes, compared to [26], resulting in reduced overhead. Speed of neighboring vehicles is a main parameter to predict lifetime of links between two vehicles. The gateway with the maximum predicted route lifetime to the requestor is selected. In [53], the discovery process makes use of predictable vehicle mobility, which is limited by traffic pattern and road layout. We conclude that reactive schemes suffer from poor scalability in discovering gateways as all vehicles have to send requests. Existing schemes (e.g., [26][51][53][54]) make use of link stability metric, which is based only on mobility metrics (e.g., relative motion between neighboring vehicles, speed, etc.), to determine paths to gateways. In city settings, such a selected route can be broken frequently owing signal conditions variation especially in the presence of obstacles. In [22], it has been proved that the number of breakages of a path increases with the number of hops in the path. Thus, the node centric view of the routes in [26][51][52][54][53] leads to frequent broken routes especially in the case of lossy channel. Consequently, many packets can be dropped, and the overhead due to route repairs or failure notifications significantly increases, leading to low delivery ratios and high transmission delays of discovery messages. Thus, vehicles that are far away from the mobile gateway transmission range will have limited or very poor Internet connectivity.

2.5.3. Hybrid approaches

In hybrid approaches [75][54], gateways advertise themselves to their n-hop neighbors ($n \geq 1$); requesters send packets to find a gateway in these advertisement areas. A hybrid gateway discovery approach is a combination of a reactive approach and a proactive approach. Thus, a hybrid approach inherits almost same limitations of both reactive and proactive approaches. Furthermore, the selection of advertisement areas depends on the dimension of the network. A small advertisement area could result in high reactive overhead, and a large advertisement area could result in high proactive overhead. In [54], the authors use the characteristics of vehicle movements (e.g., speed and direction of movement) to predict the future behavior of vehicles, and to select a route with the longest lifetime to connect to the wired network. In [75], the position of the destination and the position of neighboring nodes are used to forward data without establishing routes in the advertisement area. Any node that ensures progress toward the destination can be used for forwarding. The forwarding decision is based on the position of destination vehicle and position of one hop neighbors. However, the link to the selected node may be unreliable in harsh network conditions leading to packet loss.

2.5.4 Limitations of Internet gateway discovery schemes

Urban environment poses several challenges that hinders establishing reliable communication paths to gateways. Existing route discovery schemes are of three types: proactive, reactive, and hybrid. Almost all of them are based on two main concepts (see Table 2.2):

Table 2.2. Comparison between some gateway discovery schemes

Schemes	Flooding network		Forwarder selection criteria		category	
					proactive	reactive
	yes	no	Link recept. quality	link lifetime		
[20]	ϒ			ϒ	ϒ	
[21]	ϒ			ϒ	ϒ	
[23]	ϒ			ϒ	ϒ	
[29]	ϒ			ϒ	ϒ	
[51]	ϒ			ϒ		ϒ
[53]	ϒ			ϒ		ϒ
[26]	ϒ			ϒ		ϒ

(1) They do not consider link reception quality in establishing the route but only vehicle mobility and direction of vehicles. Indeed, they make use of link stability metrics (based mainly on speed and direction of vehicles) to select forwarding nodes and/or select any forwarder that ensures progression toward the destination. If a forwarder position is exposed to multipath effects, the message dissemination may fail resulting in unreliability.

(2) They flood all the network (reactive and proactive approaches) to search for best gateway. The gateway with longest route lifetime is selected. Yet, the selected gateway is not necessary the closest one. Higher communication hops results in longer delay and unreliability (frequent link breakages).

These observations have motivated us to propose a reliable multi-hop Internet access system (labeled RICS) (see Chapter 5) for urban scenarios. Basically, we make use of both LTE-connected vehicles (called mobile gateways) and the already deployed RSUs infrastructure as gateways. To ensure reliable multi-hop Internet access, we determine the minimum possible communication hops, from a requesting vehicle to a fixed/mobile gateway, with high reliable message dissemination. On top of the minimum communication hops, we make use of BCRB (see Chapter 4) as the gateway discovery scheme which exploits the reception quality of 802.11p wireless links to establish reliable communication paths.

2.6. Conclusion

In this chapter, we started by presenting flooding and challenges of multi-hop broadcasting in urban vehicular network. Afterwards, we reviewed the different MAC schemes (CSMA-based MAC and Repetitions-based MAC) proposed to address the issue of emergency message dissemination. The discussion shows that reliability in DSRC/802.11p based multi-hop broadcasting is still an unresolved issue. In the third part of this chapter, we described the various Internet gateway discovery schemes proposed in the literature to allow a vehicle to connect to an Internet gateway. The discussion shows proactive, reactive and hybrid approaches cannot establish reliable multi-hop communication paths to gateways in lossy channel. The main reason is that they do not consider wireless link reception quality in their operation and only rely on speed and direction of vehicles. We will devote the rest of this thesis to our contributions that aim at enhancing safety and infotainment applications in terms of reliability and delay. In Chapter 3, we detail the proposed reliable multi-hop broadcast scheme, called Reliable Emergency Message Dissemination scheme (REMD), suitable for a wide range of vehicular safety applications. In Chapter 4, we describe the new multi-hop broadcast scheme, called Bayesian networks and unipolar orthogonal Code based Reliable multi-hop Broadcast (BCRB). Finally, Chapter 5 describes the proposed Optimal Gateway Placement and Reliable Internet Access in Urban Vehicular Environments, called reliable multi-hop Internet access system (called RICS) for urban vehicular environments.

Chapter 3

Reliable Emergency Message Dissemination for Urban Vehicular Networks

Wiem Benrhaiem, Abdelhakim Hafid, and Pratap Kumar Sahu

Abstract

Vehicular safety applications based on DSRC/802.11p have strict reliability requirement (greater than 0.99). However, it is difficult to achieve high reliability in wireless medium as the transmission is vulnerable to packet collisions and interferences due to various wave propagation issues, such as signal attenuation, noise and jitter. These effects are quite predominant in urban vehicular networks in the presence of high rise buildings which makes communication in vehicular networks quite unreliable. In this paper, we propose a reliable multi-hop broadcast scheme, called Reliable Emergency Message Dissemination scheme (REMD), suitable for a wide range of vehicular safety `applications. We aim to guarantee very high reliability (e.g., 99%) in each hop, with low control overhead while keeping low end-to-end latency for time critical applications. We divide a street into multiple cells to form grid-like zones. Each zone is assigned a zero-correlated unipolar orthogonal code (UPOC) to combat hidden node problem. We apply a proactive local state processing scheme, which makes use of periodic beacons, to accurately estimate reception quality of 802.11p wireless link in each cell; then, we use this information to determine optimal number of broadcast repetitions in order to satisfy the predefined reliability requirements in each hop. In addition, to ensure reliability in multi-hop, we utilize cooperative communication. Simulation results show that REMD achieves very high reliability in lossy wireless channel. Furthermore, REMD reduces bandwidth consumption and satisfies latency requirements for time-critical vehicular applications.

Key words: Reliability requirement, multi-hop broadcasting, emergency message, urban vehicular networks, stochastic modeling.

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3.1. Introduction

The main objective of Intelligent Transportation System (ITS) is to improve road safety. Vehicular safety applications are either periodic (i.e., informing neighboring vehicles of one's state such as position, velocity, acceleration, moving direction, etc.) or event driven (i.e., a vehicle generates emergency message on detecting a hazardous road surface or an unexpected event such as accident, etc.). Dedicated Short Range Communication (DSRC) is the emerging communication standard for ITS [76][2]. Broadcast is the prevalent communication mode for vehicle safety applications [2]. On detecting an unexpected event (i.e., a traffic accident), a vehicle immediately broadcasts an emergency message to notify nearby related drivers ahead of time to allow them to take action in time. Several event-driven applications (e.g., cooperative forward collision warning) are relevant for remote drivers. Given that the transmission range of DSRC is in the order of hundreds meters [27], the emergency message has to be forwarded hop by hop to remote drivers. Figure 3.1 shows a traffic accident scenario. Car *A* (involved in an accident) broadcasts an emergency message *M* to the vehicles in the risk zone. On receiving *M*, a vehicle can slow down/brake to avoid hitting the car(s) it follows. A single uninformed vehicle, in the risk zone, may result in terrible causalities [27][28][29][30]. Thus, no driver should be deprived of information about emergency events. Consequently, high reliability of message dissemination is required. It is a known fact that the driver reaction time to traffic warning signals is on the order of 700 ms or longer [3]. Thus, it is important that the message transfer is completed with the minimum possible delay to give drivers enough time to undertake early countermeasures. Under such a fact, the delay requirement for many safety-related applications is a lower bound value compared with driver reaction time [3]. The authors, in [77], show that DSRC/802.11p-based broadcast satisfies 1-hop broadcast delay requirement. Nevertheless, 1-hop broadcast reliability is not included in the emerging DSRC standard [77] [33][31]; DSRC/802.11p-based broadcast does not support acknowledgement [32], packet retransmission and a medium reservation scheme (i.e., RTS/CTS. As a result, DSRC/802.11p-based broadcast fails to offer reliability [3].

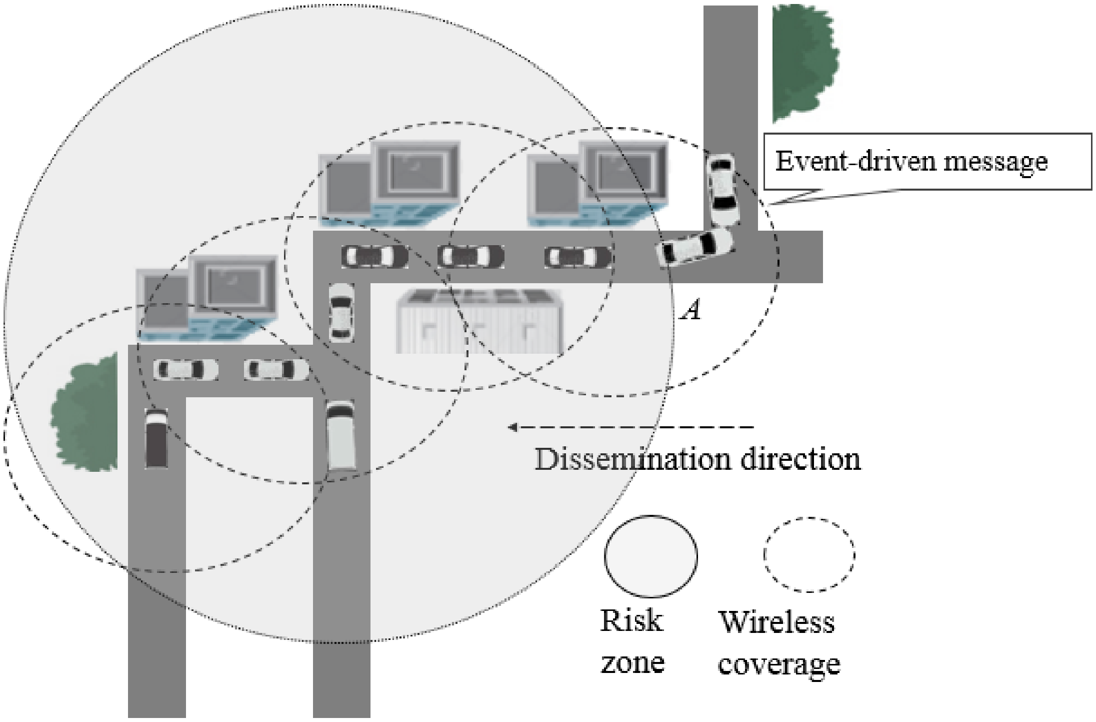


Figure 3.1. Illustration of a traffic accident scenario.

Many factors can influence probability of successful message reception in wireless communications. Typically, random loss is caused by lossy wireless channel and node mobility. Transmission in wireless medium is always vulnerable to collisions and interferences due to various wave propagation issues such as signal attenuation, noise and jitter. These effects are quite predominant in urban vehicular networks in the presence of high rise buildings making vehicular networks quite unreliable. Safety message broadcast experiences collisions with beacons either due to direct neighbors (i.e., 1-hop neighbors) accessing the channel at the same time or due to two-hop neighbors (the hidden terminal problem [49]). Furthermore, dynamic mobility of vehicles makes reliability of communication in vehicular networks more complex [42]. In the presence of all kinds of wireless network vulnerabilities, achieving reliable broadcast is a major challenge in urban vehicular networks. Definitely, the MAC layer in the updated version of the DSRC/802.11p standard [32] has strict reliability requirements [77] for safety-related applications (i.e., the probability of message delivery failure should be less than 0.01 [77]). However, the current draft of IEEE 802.11p MAC [77] [3] cannot meet such a strict reliability requirements calling for new approaches for MAC layer design [79][80][81] with the objective to guarantee broadcast reliability.

In multi-hop communication, the probability of successful message reception decreases with the number of hops [36]. IEEE 802.11 MAC scheme does not offer any specific mechanism to improve reliability in multi-hop, apart from the naïve flooding scheme [38]. However, such a solution leads to the broadcast storm problem [82] resulting in unreliability (i.e., high packet loss) and high latency [82]. Several multi-hop broadcast schemes have been proposed in the literature [40][41][60][43]. In fast schemes [40][41], the emergency message is forwarded to selected forwarders in quick successions. However, in case the forwarder has moved away or is malfunctioning, the multi-hop communication would not be possible. Other schemes [42][43][44], called efficient schemes, propose techniques to mitigate broadcast storm problem. However, these schemes don’t consider MAC layer issues in their forwarding node selection mechanism resulting in unreliable transmissions.

In [46] [83], resending the message multiple times in short intervals (time units) has been introduced to meet the requirement in terms of one-hop broadcast reliability. The basic idea is to repeat (i.e., transmit) the message multiple times within a frame in order to increase reception probability; a frame consists of L time slots. This rebroadcasting method not only increases the probability of reception but also meets latency requirements [46][83]. Random repetitions schemes like SFR [46] randomly select k repetition slots out of L. It has been proved that selecting k slots out of L increases the probability of successful message reception [42]. However, SFR [46] results in low reception probability because of hidden terminal problem.

The authors in [49] proposed to compute structured repetitions pattern based on positive orthogonal codes (POC) [62] (AKA unipolar orthogonal codes (UPOC)) in order to time separate interfering nodes. An UPOC is a binary code of fixed length L, where cross-correlation between any pair of code-words is less than a given threshold [62]. However, without evaluating the channel condition, if the number of repetitions (of a given message) is fixed per time unit, it may result in the transmission of either too few or too many packets. Too many packets lead to overhead and collisions resulting in low probability of reception. Too few packets lead to unreliability. In addition, existing structured repetitions based schemes [49][83][46] are not compatible with the CSMA/CA mechanism of DSRC/802.11p.

To overcome these limitations, we propose a reliable multi-hop broadcast scheme **(**REMD) compatible with DSRC/802.11p MAC. We have already presented a first version of our scheme in [31] and now present an extended and elaborated version. The main focus of this paper lies in achieving very high reliability in multi-hop dissemination while keeping low end-to-end latency (comparable to delay-based schemes [68] [60]) and low redundant message forwarding. REMD ensures high reliability for emergency message dissemination in lossy wireless channel. Basically, REMD divides the target area into multiple cells (fine-grained vehicle localization) to form adjacent grid-like zones and runs a proactive network state collection in each zone. REMD allows estimating, with high accuracy, the reception quality of links in the transmission range. Then, it uses this information to determine optimal number of emergency message repetitions (rebroadcasting) in order to satisfy the predefined reliability requirement in each hop. REMD combats hidden terminals using Uni-Polar orthogonal codes (UPOC). REMD carefully selects multiple forwarders and their positions in each hop. Then, it employs cooperative communication among them as a way to reinforce achieving high reliability in each hop.

The remainder of this paper is organized as follows. Section 3.2 presents related work. Sections 3.3 briefly overviews REMD. Sections 3.4-3.9 presents the components of REMD. Section 3.10 evaluates, via simulations, the performance of REMD and compares it to existing related schemes. Finally, Section 3.11 concludes the paper and presents future work.

3.2. Related work and Motivation

In this section, we review existing multi-hop broadcast schemes in vehicular networks. We also discuss one-hop broadcast schemes that use message repetition to achieve reliability.

A. Multi-hop Broadcast schemes

Existing multi-hop broadcast schemes for vehicular networks can be divided into two categories: (1) Efficient schemes and (2) Fast schemes.

1) Efficient schemes: These schemes aim at mitigating the broadcast storm problem in vehicular networks. The main idea is to reduce the number of nodes rebroadcasting the message without impacting reliability. We review two broad categories: (1) Probability-based [58] [43]; and (2) backbone-based [44] [42]. In [58], three probabilistic and timer-based broadcast suppression techniques (weighted p-persistence, slotted 1-persistence, and slotted p-persistence) are introduced. These techniques generate redundant retransmissions in dense networks resulting in large communication delay. Thus, the proposed techniques in [58] are not suitable for safety-related applications. SAPF [43] regulates the rebroadcast probability adaptively based on the vehicles speed. Proposed schemes in [58] [43] don't consider MAC layer issues (i.e., the hidden terminal problem, packet collisions, interference, link unreliability, etc.) which make forwarders selection unreliable in lossy wireless channel (i.e., city settings). Backbone-based schemes (i.e., [42][44][65]) disseminate messages based on an already formed virtual backbone structure. DBA-MAC [44] selects backbone nodes based on estimated lifetime of wireless connection among vehicles. DBA-MAC achieves low packet reception rate in the presence of lossy wireless channel. ABSM [42] makes use of acknowledgements (beacons include identifiers of the recently received broadcast messages to serve as acknowledgments) to enhance reliability. If at least one neighbor doesn't acknowledge the message, the backbone node performs more retransmissions. In dense networks, ABSM [42] performs redundant retransmissions due to increased packet collisions. In city environment, the performance of wireless links is severely degraded due to channel fading (i.e., surrounding buildings and mobility of nodes impact radio propagation) resulting in weak connectivity between backbone nodes. Creation and maintenance of the backbone structure (i.e., links of the backbone nodes) generate high communication overhead.

2) Fast schemes: Several schemes [60] [33] [40] [41] have been proposed for fast message dissemination. The main idea is to reduce the number of hops resulting in fast message propagation. To achieve this, these schemes select the farthest neighboring node from the sender in the message propagation direction as the next relaying node. Several methods have been proposed to elect the farthest forwarding node. UMB [60] divides the transmission range into several sectors. After successfully receiving a message, a vehicle generates a black burst (channel jamming signal) whose duration is proportional to the distance of its sector. Then, it computes a waiting time inversely proportional to its distance. The vehicle located in the farthest sector is elected as the forwarder. BPAB [33] is based on iterative binary partitioning to find the farthest sector containing possible forwarder. In BPAB, a vehicle generates a black burst signal to guarantee successful message reception at the farthest vehicle. UMBP [64] makes use of iterative partition, mini-slots, and black-burst to select remote neighboring nodes. A single forwarding node is chosen using asynchronous contention among remote neighboring nodes. However, using black burst would not be very effective in vehicular networks; indeed, a receiver cannot distinguish between two black bursts generated simultaneously from different road segments.

3P3B [63] allows the farthest possible vehicle in the farthest sector from the sender node to perform forwarding. In “Abiding Geocast” [40] and PAB [41], each node receiving a packet determines the distance with respect to the sender. Then, it picks a waiting time inversely proportional to the distance. The farthest node is whose time expires first; note that the sender is aware of its neighbors through received beacons. However, the time gap between sender beacon sending time of a node and the time at which that node becomes a forwarder may be very long. In such situations, the forwarder may not be within the range of the sender. Thus, the sender remains unaware of message dissemination and starts rebroadcasting. PMBP [61] selects the farthest forwarding node according to its distance to the sender. Similarly, ROFF [62] selects the farthest node using distance to the sender. However, it is a known fact that one hop broadcast reception rate is lower in farthest positions due to channel fading [77]. As a result, existing forwarding node selection methods (e.g., [64] [61] [63]) perform multiple timer-based retransmissions which does not satisfy delay requirements of safety-related applications. CLBP [67] selects a single forwarding node based on geographical locations, physical-layer channel conditions, and moving velocities of vehicles. Before sending data packet, CLBP makes use of BRTS/BCTS packets to prevent hidden terminal problem. However, a single BRTS packet is vulnerable to interference in a city scenario. To ensure reliable message delivery to forwarder, the latter sends an acknowledgement (ACK) frame back to the sender. However, acknowledgement (ACK) mechanism is generally not robust under harsh channel conditions. More specifically, ACK messages are prone to interferences. In addition, in most of aforementioned schemes (i.e., [61] [62] [63][64]), a single selected forwarding node may change direction or be malfunctioning. In such a situation, the proposed schemes will not properly work. They suffer from unreachability of intermediate nodes (i.e., located in the area between two successive forwarding nodes) problem; these nodes perform overhearing to receive messages. The overhearing approach does not guarantee successful message reception. As a result, broadcast reception rate is low in lossy wireless channel. In the literature, few schemes (i.e., [68] [45]) have proposed solutions to improve reliability of intermediate nodes. Oppcast [68] selects farthest possible neighboring node based on acknowledgements (ACK) and retransmissions to forward the message to next hop. To improve packet reception ratio for intermediate nodes, Oppcast elects ‘makeups’ (intermediate forwarders). The makeups rebroadcast the message to enhance the packet reception rate PRR in each one-hop area. However, the ‘makeups’ are selected, based on their distance to the sender. In adverse network conditions, selected makeups may have low reception quality resulting in packet loss. Oppcast records low PRR for intermediate nodes. EMDOR [45] selects a single forwarding node each hop to disseminate message to next hops. The selected forwarding node transmits an ACK message on behalf of other receiving nodes. EMDOR improves the broadcast reliability of intermediate nodes by allowing them to overhear an ACK packet; if a node overhears an ACK, but has not received the corresponding message, the node considers that the emergency message is lost and requests the selected node to perform rebroadcasting. The retransmission overhead could be very large. This is because different nodes could lose different packets and therefore the sender node has to retransmit all these lost packets. To conclude, fast schemes are more concerned by delay more than reliability. Consequently, emergency messages are received with minimum latency at the cost of lower reliability.

Existing multi-hop broadcast schemes (i.e., [60] [33] [40] [41] [61] [62]) are exposed to the following problems: (1) one forwarding node is selected per hop; and/or (2) unreachability of intermediate nodes problem. In Figure 3.2(a), source *A* selects farthest node *D.* Node *A* makes use of ACK and its associated timer-based rebroadcasting to select node *D*. In lossy wireless channel, ACK is vulnerable to packet loss. Furthermore, the number of retransmissions is almost unknown. To protect data packet, source *A* may make use of RTB/CTB; however, a single CTB may, in turn also, be vulnerable to packet loss in lossy wireless channel. Figure 3.2(b) shows that selected forwarding node *D* may be out of the transmission range or malfunctioning when data packet transmission occurs. Thus, the dissemination process can be stopped. Figure 3.2(c) shows that intermediate node *F* may have low link reception quality and does not properly decode the data packet. The sender *D* cannot detect such a failed reception.

For CSMA-based MAC (i.e., [60] [33] [40] [41] [61] [62]), the successful reception of a packet by the farthest neighbor does not guarantee the successful reception by all other neighbors. Recently a family of repetition-based MAC protocols have been proposed for the one-hop broadcasting of safety messages in vehicular networks.

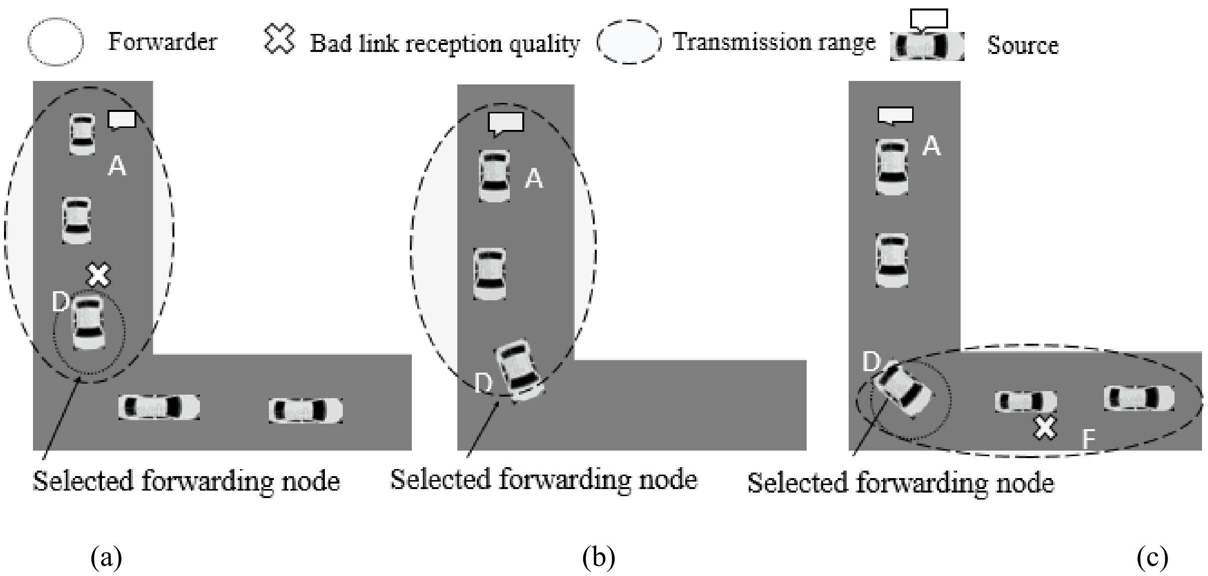


Figure 3.2. Problems experienced by most of the multi-hop broadcasting schemes. (a) –(b) Single forwarder problem (c) Intermediate nodes reachability problem

B. Repetition-based schemes

Repetition-based broadcast schemes of safety messages has been first introduced in [77] [46]. More repetition variants are presented in [46]. The objective of message repetition is to meet one-hop requirements in terms of reliability and latency [77] [46]. Each vehicle uses a repetition-based MAC in order to achieve high reception probability. Consider time is divided into frames. Each frame in turn is divided into k time slots with length equal to the transmission time of a single packet. Repetition-based schemes can be divided into two broad categories:

1) *Random repetitions* [46] [71]*:* Each packet is transmitted a number of times inside the frame. SPR [46] transmits the packet in each timeslot in a frame with probability *p*. In this approach a packet may be transmitted L times or not transmitted at all. SFR [46] randomly chooses the transmission slots. It reports higher reception probability compared to SPR. Recently, this result has been used to design reliable multi-hop broadcast schemes (i.e., [71]). FR-EMD [71] adjusts the number of repetitions based on the network density. However, in city settings, whatever the number of broadcast repetitions, FR-EMD does not guarantee high reliability in lossy wireless channel. Indeed, FR-EMD does not take into account signal propagation issues (e.g., slow-fading) caused by obstacles. Furthermore, FR-EMD does not consider hidden

terminal problem. In situations of large number of transmissions, randomly selecting repetition slots may result in high packet loss rate (i.e., collisions/interference).

2) *Structured repetitions* [49][73]: Transmission/repetition patterns (timeslots in which a node is allowed to transmit in a frame) are computed based on positive orthogonal codes (POC), known as unipolar orthogonal codes (UPOC). An UPOC [84] represents a binary sequence $\{0,1\}$ with small cross-correlation, where cross-correlation between any pair of code-words is less than a given threshold [84]. In POC-MAC [73], the distribution of repetition patterns to nodes uses considerable channel resources (i.e., available codes are acquired through message-passing) in high density networks. In lossy channel, the exchanged messages (message-passing between vehicles to update codes availability information) can be lost. This may result in erroneous code assignment (i.e., two neighboring nodes may allocate same code) resulting in unreliability. Furthermore, the authors compute the probability of successful transmission without taking into account signal propagation issues. CPF [49] extends POC-MAC [73] for multi-hop emergency message dissemination in highway scenarios. In lossy wireless channel, selected forwarders may have bad link reception quality resulting in failed reception; whatever the number of repetitions, if a forwarder position is exposed to shadowing and multipath effects, the message dissemination will be stopped resulting in unreliability. CPF doesn't guarantee high broadcast reliability in lossy channel. Indeed, if fixed number of message repetitions is forwarded over a frame, they may be sending either too few or too many packets.

In addition, structured repetition-based schemes [49][73] are not compatible with emerging DSRC/802.11p. In this paper, REMD provides a solution to existing reliability issues, by introducing a proper design of emergency message repetitions and a multi-hop dissemination strategy compatible with DSRC/802.11p. More specifically, REMD allows estimating/predicting, with high accuracy, the link reception quality. Then, it uses this information in order to guarantee:

(1) One hop reliability of 802.11p-based broadcast:

- By carrying out an optimal number of emergency message repetitions. Repetition patterns are computed based on Uni-polar orthogonal codes (UPOC) to combat hidden terminal problem.

(2) Multi-hop reliability:

- By carefully selecting multiple forwarders and their positions, each single hop.
- By employing a cooperative communication scheme that allows forwarders to retransmit the emergency message an optimal number of times with the objective of ensuring high retransmission reliability.

3.3. REMD: An Overview

REMD is designed to disseminate emergency messages with very high reliability in urban vehicular network. The main idea of REMD is to guarantee broadcast reliability (e.g., r_{th}=99%)) [27] at each hop by performing an optimal number of broadcast repetitions. Basically, REMD estimates, with high accuracy, the reception quality of wireless link in the transmission range *Tr*. Then, it uses this information to compute an optimal number of message repetitions and to select multiple forwarders and their positions at each hop. The forwarders of each hop perform cooperative communication to reinforce achieving high broadcast reliability.

A. Assumptions

We assume that (1) vehicles are moving on urban streets; a scenario where a source node with a generic emergency message *M* that requires multi-hop transmission is intended for all nearby vehicles in a geographical area; (2) vehicles are equipped with Global Positioning System (GPS) and digital road maps; (3) vehicles are equipped with IEEE 802.11p [2] wireless technology and computation capabilities; (4) obstacles (e.g., buildings, moving vehicles) exist; they impact communication among vehicles; and (5) the factors causing failures of message transmissions are temporary or intermittent (e.g., failure of 802.11p/GPS in a vehicle is not considered).

B. Network model and definitions

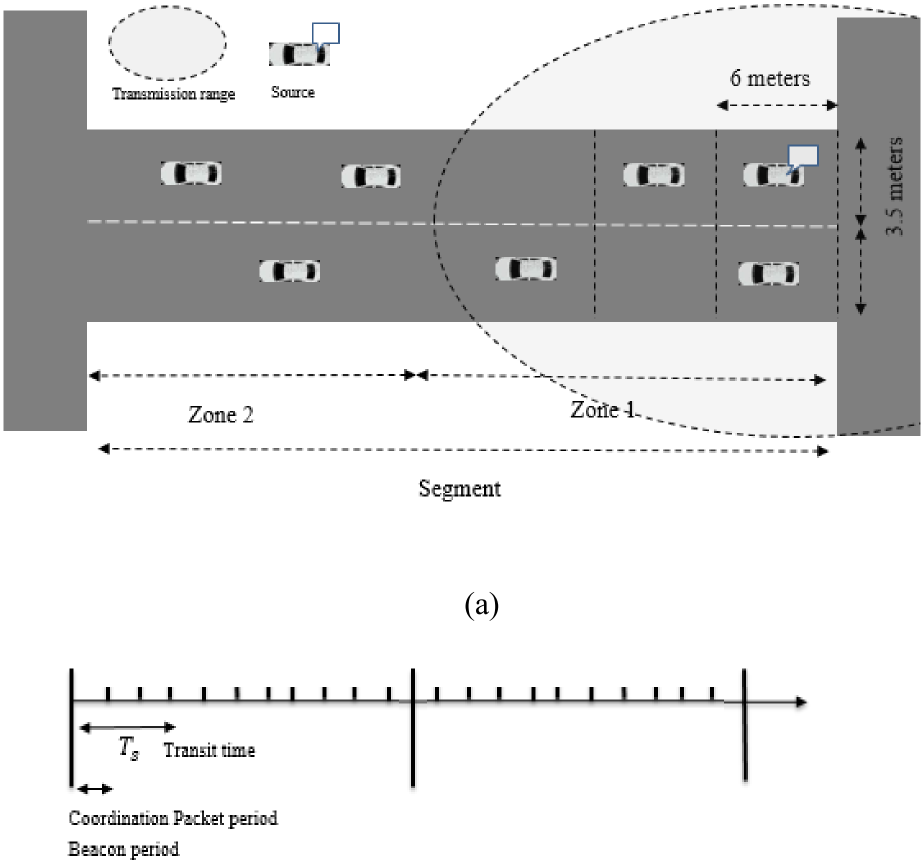
In the following, we present the definitions of the relevant terms used to describe REMD (See Figure 3.3(a)).

- **Source node:** It defines the vehicle that detects an unexpected event.
- **Target area:** It defines the geographical area that includes all vehicles approaching/driving, towards the source, that are intended recipients of the emergency message generated by the source node
- **Segment***:* It defines the area between two road intersections.
- **Zone:** It defines a static portion of the segment whose length is same as the transmission range of a vehicle. Based on its length, a road segment is divided into a number of zones.

- **Cell:** It defines a static partition of a zone with predefined length (e.g., length of a Car $y = \sim 6$ meters [104]). A cell represents a possible vehicle position (a fine-grain localization of vehicles). Assuming the lowest speed in the city is equal to 10 Km/hour, the minimum distance between two vehicles is $\frac{10000*2}{3600} \cong 5.55 \text{ meters}.$ Thus, there will be either 1 vehicle or no vehicle in each cell. In each zone, cells are identified/numbered 1, 2, 3, etc.
- **Transit time:** It defines the time interval that a vehicle takes to transit a cell (a vehicle position). If Ve is the vehicle velocity, the transit delay T is computed as follows:

$$T = \frac{6}{Ve} \tag{1}$$

- **Regular vehicle:** It defines a passing vehicle. During T, such a vehicle records cell information. Then, it includes this information in its next beacon. We use the term regular vehicle or vehicle interchangeably to denote a passing vehicle.
- **Coordinator:** It defines a vehicle located around the center of a zone to continuously process received beacons of vehicles in the effective zone (i.e., the current zone). There exists a coordinator per zone.
- **Coordination packet (CP):** It defines a periodic packet transmitted by the coordinator. The coordinator transmits periodic CPs instead of periodic beacons (See Figure 3.3(b)). CP includes the status information of the coordinator (position, velocity, direction, etc.) together with information it processed. The transmission power of CP is two times the beacon's one.
- **Sender:** It defines the current broadcast node (a node that intends to transmit the emergency message). The source is a sender when it first broadcasts the emergency message.



(a)

(b)

Figure 3.3. Network model: (a) Target area structure, (b) Time schedule

C. Scheme Components

The objective of REMD is to determine an optimal number of message repetitions and forwarders, together with their positions, to achieve reliability requirements. It consists of an initialization phase, called IN, and 5 key phases: (1) Data Collection (DC); (2) Local State Processing (LSP); (3) Broadcast Reliability guarantee (BR); (4) Forwarders Selection (FS); and (5) Cooperative one-hop reliability guarantee (C-reliability). IN is executed once to assign a zero-correlated Uni-Polar orthogonal code to each zone. DC and LSP run continuously whereas BR, FS and C-reliability run only when an event requiring a message to be disseminated to vehicles in a target area occurs. It is important to note that REMD is also applicable for safety applications that rely on one-hop message broadcast. In that context, FS and C-reliability phases are omitted. The phases are briefly described as follows:

(1) **DC:** It is executed by regular vehicles; more specifically, a regular vehicle records its state information (i.e., packet collision rate and average signal power attenuation). Then, it includes this information in its periodic beacons. The objective of this phase is to provide the coordinator with information about wireless channel state in its effective zone.

(2) **LSP:** The coordinator executes LSP to process beacons received from neighboring vehicles, to estimate/predict link reception quality of 802.11p wireless link of vehicles in each zone; then, it includes this information in next CP.

(3) **BR:** It is executed at the source and at the forwarders. Using recent received CPs, the source (or the forwarder) computes optimal number of broadcast repetitions that satisfy reliability requirements in its transmission range.

(4) **FS:** It is executed at the source and at a specific forwarder. Using recent received CPs, the source (or the forwarder) selects multiple forwarding nodes and their positions in its transmission range.

(5) **C-Reliability:** The forwarders of same hop execute C-reliability, in a distributed fashion, and coordinate to select next-hop relays (forwarders). More specifically, the forwarders perform cooperative communication to send/repeat the emergency message an optimal number of times with the objective to ensure high reliability in next hop.

3.4. Initialization Phase: IN

To combat hidden terminal problem, REMD uses Uni-Polar orthogonal codes [84]. More specifically, REMD assigns to each zone a specific code (repetition pattern) obtained from zero-correlated Uni-Polar orthogonal codes in order to time-separate interfering nodes (See Figure 3.4). Let $\xi = (L, \varpi, \lambda)$ be a set of UPOCs, where L is the code length, ϖ is the code weight and λ is the cross-correlation [84]. Let x= $(x_1, x_2, \dots, x_L)$ and y= $(y_1, y_2, \dots, y_L) \in \xi$ be two codes such that $x \neq y$. Let τ $(1 \leq \tau \leq L-1)$ be a circular displacement. The cross-correlation property is defined as follows: $\sum_0^{L-1} x_i * y_{i\oplus\tau} \leq \lambda$. A repetition pattern represents a binary sequence of length L in which bit 1 denotes a transmission and bit 0 represents an idle timeslot. In each timeslot, if a node is not transmitting, it switches to idle mode. The code assignment scheme must ensure that cross-correlation property λ $(0 \leq \lambda \leq \varpi - 1)$ with 2-hop neighboring nodes is zero. The average segment length is smaller or equal to 500 m [85]. In the model of city roads network used in this work, the average road segment length is double the transmission range (transmission range is 250 m [86]). Hence, a node along a road segment can interfere with up to 4 other nodes along adjacent road segments (2 nodes in two zones on the same road and 2 nodes in two zones along the perpendicular roads). Thus, at least 5 codes (i.e., $|\xi| = 5$) having zero correlation are required. Johnson [87] provides an upper bound for the size of codes $|\xi| = \left\lfloor \frac{L}{\varpi} \right\rfloor$, where L is the code length and $\boldsymbol{\varpi}$ is the code weight.

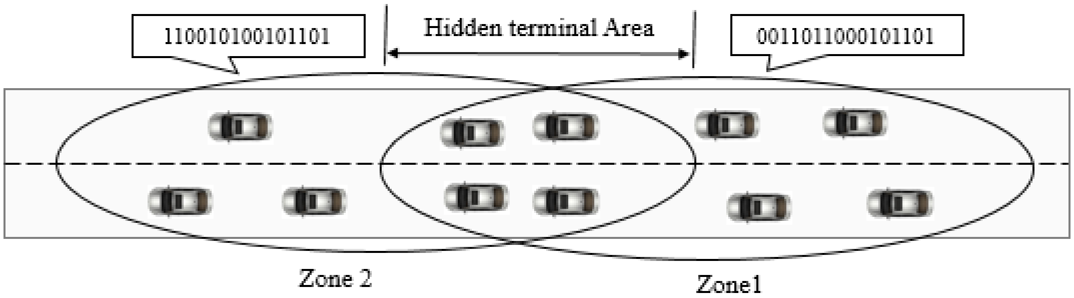


Figure 3.4. Unipolar-orthogonal codes in two adjacent zones

3.5. Data Collection: DC

DC allows collecting packet loss rate (PL) and signal power attenuation rate (PA). DC is executed at regular vehicles. During the transit delay T, a vehicle transiting a cell may receive multiple packets. At the end of T, the vehicle computes PL (see Equation 2) and PA (see Equation 3) for that cell. The packet loss rate of cell x at time t is given as follows:

$$Pl(x,t) = \frac{NL}{Nt} \tag{2}$$

where Nt is the total number of packets and NL is the number of lost packets. To compute PL, we assume that (1) The number of packets resulting from 3 or more packets colliding at any instant t is negligible [88]; and (2) The number of packets that fail to be detected by the receiver's radio device is negligible [89]. Therefore, the number of lost packets NL detected by vehicle v, during T, is equal to the sum of the number of non-decodable messages, n_1, from senders located in the interference range of v and the number of collisions, n_2, due to "real" collisions of packets emitted from two senders that are both in range of the receiver ($i.e., NL = n_1 + 2 * n_2$). Using Equation (2) requires that the vehicle determines the "real" number of packets Nt sent by nodes in range or in interference range; the “real” number of packets includes packets that didn’t reach the vehicle; in practice, a receiver is unable to record such information. The “real” number of packets Nt is equal to the sum of the number of lost packets NL and the number of successfully received packets Nr ($i.e,. \ Nt = NL + Nr$). The signal power attenuation rate PA of cell x at time t is expressed as follows:

$$PA(x,t) = \frac{1}{Nr} * \sum_{i=1}^{i=Nr} \left(\frac{X_0(d_i)}{Tx}\right) \tag{3}$$

where d_i is the distance to neighbor i,, $X_0(d_i)$ is the power attenuation rate of a packet sent by neighbor i, and Tx is the transmitted signal power. Upon a successful reception of a packet, the vehicle records the packet’s received signal strength indicator (RSSI) and its transmitted power Tx. It is worth noting that signal power attenuation, reception power and transmitted power are only available for successfully received packets. In a realistic channel model, like Rayleigh, the RSSI value at distance *d* from the transmitter is given by:

$$RSSI(d) = Tx - Los(d_0) - 10 * \rho * log_{10}\left(\frac{d}{d_0}\right) + X_0 \tag{4}$$

where Tx is the transmitted power in decibel (DB), $Los(d_0)$ is the path loss at a reference distance (i.e., d_0), ρ is the path loss exponent and X_0 denotes the signal attenuation in decibel. X_0 is modeled as random variable with Rayleigh distribution [90]. The value of ρ can be set depending on the propagation environment [90]. Our objective is to extract the value of the attenuation effect X_0 from the received RSSI value. To achieve this, we consider one sender and one receiver, spaced by m meters. The transmitter emits only one packet to be exposed to only fading and path loss effect (i.e., $X_0 = 0$). In this case, the receiver records signal power degradation ($Tx - RSSI$). Then, it calculates the average attenuation per meter (e.g., for d=20 meters and $0.08db$; we obtain signal power degradation rate $\alpha = \sim 0.004 \ db/ \ meter$). Thus, the receiver is able to extract X_0 from RSSI (i.e., $X_0(d) = RSSI(d) - \ \alpha * d$). At the end of T, regular vehicle includes PL and PA in its next beacon.

3.6. Local State Processing: LSP

This phase estimates link reception quality Q in the transmission range. LSP is executed at the coordinator node. The coordinator acts as a zone manager. It is in charge of processing exchanged beacons. Indeed, the zone manager provides a source node with data corresponding to its range. A coordinator is chosen dynamically through exchange of beacons. To select a coordinator, we introduce a status flag in beacons, which, if set, represents a coordinator vehicle; otherwise, it represents a regular vehicle. We define start coordination position S-p as one-quarter of the transmission range away from the beginning of the zone and the last coordination position L-p as three-quarter of the transmission range away from the beginning of the zone. If a vehicle finds itself as the closest vehicle to the position S-p, it sets its status to coordinator; a flag is included in periodic beacons to represent the status of a vehicle (i.e., coordinator or regular vehicle). Upon reaching the position L-p, it resets its status (i.e., becomes regular vehicle) and allows another vehicle located in S-p (or nearby) to be the zone manager. At any time, there is only one coordinator per zone. Upon receipt of a beacon from a vehicle located in cell x at time t, the coordinator extracts (1) $PL(x,t)$ to measure the quality of wireless link in cell x (see Equation 5); and (2) $PA(x,t)$ to compute an equivalent packet loss rate $ePL(x,t)$ (see Equation 6). Let us analyze the variation, over time, of average attenuation (PA) and packet loss rate (PR) for cell 'A' (see Figure 3.5). By using 4th order polynomial curve fitting [91], we show that PA and PL have similar variations (see Figure 3.5); they have linear correlation. We extract the conversion ratio τ (correlation coefficient) that represents the average attenuation to the average packet loss over a period of time. Therefore, the reception quality of 802.11p wireless link $\mathrm{Q(x,t)}$ at time t can be expressed as follows:

$$Q(x,t) = 1 - PL(x,t) \tag{5}$$

In case of controlled channel condition, reported PL values may be equal to zero. Therefore, the reception quality of 802.11p wireless link $\mathrm{Q(x,t)}$ at time t can be expressed as follows:

$$Q(x,t) = 1 - ePL(x,t) = 1 - \tau * PA(x,t) \tag{6}$$

Link reception quality $Q(x,t)$ changes over time due to the dynamic nature of vehicular networks; thus, if the source node uses reception quality measured at t1, by the coordinator, to execute actions at t_2 (t_2>t_1), wrongful decisions may be taken (e.g., selection of forwarders). Thus, before transmission of CP at t_2, the coordinator estimates/predicts, with high accuracy, link reception quality at t2 based on its quality history (i.e., quality at t_1 and earlier). The coordinator makes use of PA and PL, previously measured (see Figure 3.5) in its neighboring cells (i.e., in its transmission range), to predict future values of PA and PL, with high accuracy.

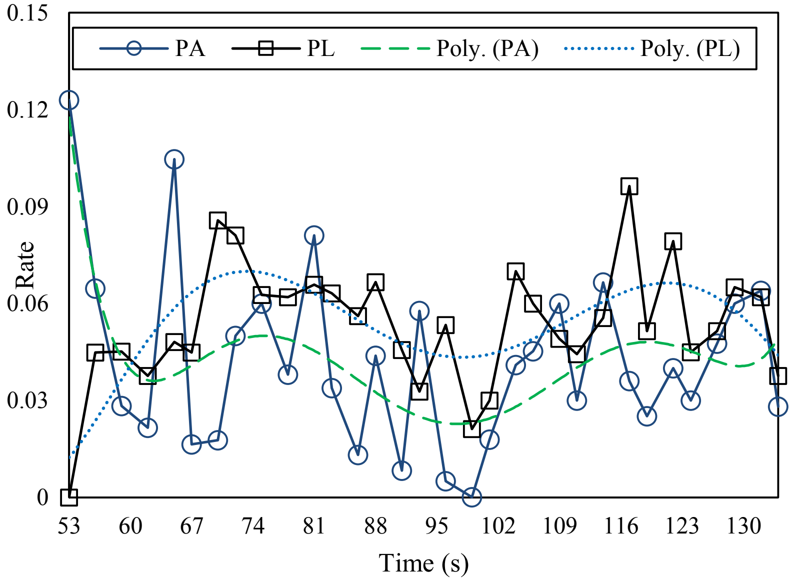


Figure 3.5. Distribution of PA and PL over time in a cell

For prediction, it extends the historical time-series PL and PA to future periods using curve-fitting. To achieve this, let us do a polynomial modeling of PL and PA values for a cell A. Let $P(t)$and $R(t)$ denote kth order polynomials that represent PL-trend and PA-trend respectively. $P(t)$ and $R(t)$ are defined as follows:

$$P(t) = \mathrm{a}_0 + \mathrm{a}_1 t + \mathrm{a}_2 t^2 + \cdots + \mathrm{a}_k t^k \tag{7}$$

$$R(t) = \mathrm{b}_0 + \mathrm{b}_1 t + \mathrm{b}_2 t^2 + \cdots + \mathrm{b}_k t^k \tag{8}$$

The problem of determining $P(t)$ is reduced to that of determining the coefficients a_i, where $0 \leq i \leq k$, as accurately as possible using experimental results and taking into account experimental errors. Quantifying the error for the polynomial trend using the least squares approach is as follows:

$$err = \sum(d_i)^2 = \sum(PL(t_i) - P(t_i))^2 \tag{9}$$

Note that it is particularly difficult to accurately estimate/predict the channel condition in vehicular networks due to the frequently changing network environment [92]. Although there are some limitations for the polynomial modeling based estimation, we can minimize the error (Equation (9)). Similarly, coefficients in Equation (8) can be estimated. The approximation of PL and PA variations are then $P(t)$ and $Q(t)$. Therefore, the coordinator sets a local state map (LSM), and includes it in its next CP. LSM consists of link reception quality $Q(x,t)$ of vehicles in the effective zone.

3.7. Broadcast Reliability: BR

This phase allows guaranteeing predefined reliability r_{th} in transmission range. To achieve this, the vehicle rapidly repeats the message an optimal number of times, using the repetition pattern of its effective zone, with the objective to enhance reception probability per-receiver. More specifically, we consider a useful message lifetime T whose value is smaller than human reaction time; the vehicle repeats broadcasting the packet multiple times only within T. Let τ be the time needed to perform one repetition ($\tau = 1$ time slot). The transmitter evenly splits the lifetime into L time slots, where $L = \left\lfloor \frac{T}{\tau} \right\rfloor$. Each repetition of the message is a new packet. Cell transit time T_s ranges between 0.2 s and 0.4 s while message lifetime T is less than 0.5s. Link reception quality $Q(x,t)$ represents reception probability per slot.

$$p(x) = Q(x,t) \tag{10}$$

During T, the sender performs n repetitions. Excessive repetitions might cause congestion leading to collisions [48]. Therefore, an optimal number of repetitions n_{opt} must be determined. Let Ng be the number of neighbors in transmission range, t_k $(1 \leq k \leq L)$ be a random variable that indicates that k time slots are picked (i.e., k repetitions are performed) and X_i $(0 \leq i \leq Ng)$ be a random variable taking values 0 and 1. X_i follows a Bernoulli random variable $X_i \sim \beta(p(x))$

with reception probability p_i, associated with receiver i. The probability mass function (p.m.f) of X_i is shown in Eq,(11). Let Y_i^k be a geometric random variable $Y_i^k \sim \text{geo}(p(x))$associated with receiver i, $(1 \leq i \leq Ng)$. The geometric random variable Y_i^kreturns the number of Bernoulli trials (repetitions) as expressed in Equation (12). Probability of first success at the k^{th} repetition, for $k \geq 1$, is given in Equation (13).

$$p(X_i = 1) = p_i = Q(x,t) = 1 - p(X_i = 0) \qquad (11)$$

$$Y_i^k = k \Leftrightarrow \left(X_i^1 = 0, X_i^2 = 0, X_i^{k-1} = 0, X_i^k = 1\right) \quad (12)$$

$$P(Y_i = k) = p_i * (1 - p_i)^{k-1} \qquad (13)$$

The integer linear programming (ILP) [93] of the broadcast reliability (BR) problem can be expressed in Equations (14)-(16).

$$\text{Max}_{1\leq\text{i}\leq\text{Ng}}\left(\text{Min}_{1\leq\text{k}\leq\text{L}}\left(Y_i^k * t_\text{k}\right)\right) \qquad (14)$$

S.c.t

$$\frac{1}{N} * \sum_{k=1}^{k=L}\left(\sum_{i=1}^{i=Ng}\left(X_i^k * t_k\right)\right) \geq r_{th} \qquad (15)$$

$$t_k, X_i^k \in \{0,1\} \qquad \text{for all i, k} \qquad (16)$$

The objective function (14) minimizes the number of repetitions. Constraint (15) guarantees broadcast reliability requirement r_{th}. We define the broadcast reliability metric as the ratio of the number of vehicles, in the transmission range, that successfully receive the message within its lifetime T, to the number of total neighbors. This metric is called packet reception rate (PRR). PRR is the common deterministic metric to measure one-hop broadcast reliability protocols [76]. Hence, constraint (15) can be written:

$$PRR \geq r_{th} \qquad (17)$$

Constraint (16) is the integrity constraint of the decision variables. BR is a linear max-min optimization problem [93]; we solve this problem using an iterative procedure. The main idea of the solution is to increment repetitions by 1 and compute PRR. The number of repetitions (Equation (14)) achieves its minimum value n_{opt} the first time PRR becomes greater than the predefined reliability threshold r_{th} . We quantify PRR before a message transmission occurs. In the first repetition, let us suppose Bernoulli random variables X_i $(1 \leq i \leq Ng)$ are independent such that p_i $(1 \leq i \leq Ng)$ are not all identical. Let $S = \sum_{i=1}^{i=N} X_i$ be the distribution of their sum. The distribution of S is known to be a Poisson's Binomial Distribution (PBD) [95]. The number of successful receivers is k out of Ng. The probability of having k $(1 \leq k \leq Ng)$ successful receivers out of a total of Ng can be expressed as the following probability mass function (p.m.f) [103]:

$$P(S = k) = \sum_{A \in \binom{k}{Ng}} \prod_{i \in A} p_i * \prod_{j \in} \left(1 - p_j\right) \qquad (18)$$

where A^c is the complement of A. In a sequence of n independent repetitions each of reception probability p(x), we redefine the Bernoulli random variable X_i , associated with receiver i, that takes the value one if at least one successful packet reception occurs. Reception probability $p_n(x)$ is defined as follows:

$$p_n(x) = 1 - \left(1 - Q(x,t)\right)^n \qquad (19)$$

$$p_n(x) > Q(x,t) \qquad (20)$$

The number of trials remains Ng. The probability mass function (p.m.f) of the number of receivers can be reformulated as follows:

$$P(S = k) = \sum_{A \in \binom{k}{Ng}} \prod_{i \in A} [1 - (1 - Q(x,t))^n] * \prod_{j \in \overline{\binom{k}{Ng}}} (1 - Q(x,t))^n \qquad (21)$$

In practice, the sum over $\binom{k}{Ng}$ in Equation (21) has a high computational time and space requirements. For example, for Ng=40, the sum generates more than 10^{30} elements. Several solutions have been proposed to calculate probabilities in Equation (21). Le Cam theorem [96] establishes two basic hypothesis for Poisson approximation to the Poisson binomial distribution in the Poisson limit theorem [96]. If $p_i \rightarrow 0$ and $Ng \rightarrow +\infty$, the mean value $\lambda = p_i * Ng$ remains constant. Therefore, $p(S = k)$ in Equation (21) equals to $e^{-\lambda}\frac{\lambda^k}{k!}$. However, we cannot apply Le Cam theorem in vehicular networks since, in this case, $p_i \nrightarrow 0$ and $Ng \nrightarrow \infty$; indeed, applying Poisson approximation to solve Equation (21) will result in less accurate results. Thus, we turn to find the exact PBD. To compute Poisson Binomial probability mass function (p.m.f) (see Equation (21)), we make use of Fast Fourier Transform (FFT) based algorithm [97] to speed up the computation. More specifically, we adapt the algorithm in [98] to derive a simplified exact formula of Equation (21). The adapted algorithm is labeled PMF-FFT. Basically, PMB-FFT makes use of the characteristic function of the random variable $S = X_1 + X_2 + \cdots + X_n$ to derive Inverse Discrete Fourier Transform (IDFT) equation of the sequence $\{p(s = 1), p(s = 2) \ldots p(s = Ng)\}$. Then, PMB-FFT applies the FFT algorithm [54] to both sides of the derived IDFT equation to get p.m.f of the random variable S. The time complexity of FFT (and hence of PMF-FFT) is $O(N \times \log(N))$ [97]. Let ω_n define the resulting vector of PMF-FFT for the nth repetition. Hence, ω_n represents the exact distribution of the distribution. The number of successful receivers k corresponds to the maximum value ∂ , $1 \leq \partial \leq Ng$, starting from which the cumulative sum of probability mass function (p.m.f) (Equation (21)) equals 0.99 . By this way, the number of successful receivers k is obtained with a 99% guarantee. This value is easily obtained using Equation (22). Packet reception rate (PRR) is expressed in Equation (23). The number of repetitions (Equation (14)) achieves its minimum value n_{opt} the first time PRR (Equation (23)) becomes greater than the predefined reliability threshold r_{th} $(PRR(n) \geq r_{th})$.

$$\partial(n) = \left\{ \max_{1 \leq x \leq Ng}(x)\ ; \left(\sum_{k=x}^{Ng} (\omega_n(k)) \right) \geq 0.99 \right\} \tag{22}$$

$$PRR(n) = \frac{\partial(n)}{Ng} \tag{23}$$

A vehicle joining a road segment gets the repetition pattern of its effective zone by using the road ID (In a numerical map, each road segment is given a road ID) and its position. Once an event occurs, the vehicle computes its optimal number of repetitions n_{opt}. Then, it maps this number to the repetition pattern of its effective zone (i.e., the vehicle selects the first n_{opt} transmission slots out of ϖ slots).

To perform n_{opt} repetitions, we design an overlay, called MAC Repetition Layer (MRL), on the standard MAC Carrier Sensing [99]. MRL is responsible for generating broadcast repetitions. MRL resides between standard MAC layer and Logical Link Control (LLC) layer. The state machine of MRL is shown in Figure 3.6. MRL consists of 3 states: (a) *Repeat*; (b) *Drop;* and (c) *Idle*. If a packet is received from LLC layer, MRL switches from *Idle* to *Repeat*. Here, MRL generates n_{opt} packets, associates them to the first n_{opt} $(1 \leq n_{opt} \leq L)$ time slots (FIFO) of the repetition pattern and transmits them to MAC layer; then, it goes back to *Idle*. In case a packet is received from MAC, MRL switches from *Idle* to *Discard*. Here, MRL checks whether the packet is new. If yes, the packet is transmitted to LLC; otherwise, it is discarded.

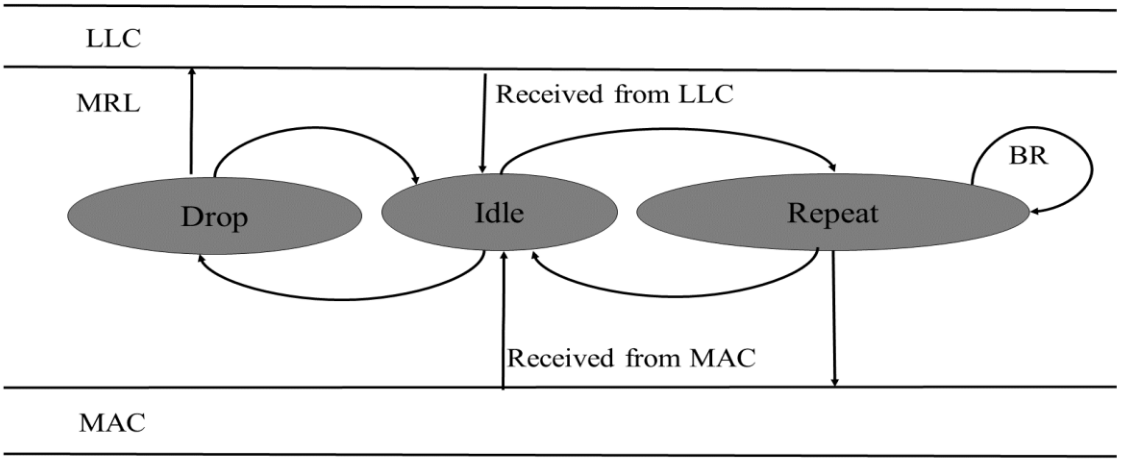


Figure 3.6. State machine of MAC Repetitions Layer (MRL)

3.8. Forwarders selection

To relay the message to next hop, REMD executes FS. The main idea of FS is to select multiple next-hop forwarders having best link reception quality $Q(x,t)$). Let n_F be the number of forwarders. Multiple forwarders allow avoiding single forwarder limitations; if only one vehicle is chosen as a forwarder and if that vehicle malfunctions or moves away (i.e., leaves the road segment) the message dissemination will be stopped. For simplification, we take number of repetitions n_{opt} as a reasonable value for n_F. To ensure successful message reception, forwarders should have high reception probability. Furthermore, it is a known fact that forwarders locations should be close to the border in order to reduce multi-hop latency. FS consists of two steps:

- ✓ Reception-based selection:

The sender makes use of link reception quality information to select forwarders. Forwarders having good link reception quality are better choice to successfully receive the message and retransmit it. Consider neighbors' information is available (i.e., using exchanged beacons). Let v^{Ng} denotes the set of cells in transmission range having vehicles. For each $x \in v^{Ng}$, the sender extracts the corresponding link reception quality $Q(x,t), 1 \leq x \leq Ng$ from the most recent CP packet and picks the best n_F elements of v^{Ng} (in terms of link reception quality); then, it creates a set v^q that includes these elements ordered from best to worst (in terms of link reception quality).

- ✓ *Position-based selection:*

In order to reduce hop count, the sender ensures that the forwarders locations are close to the border. To achieve this, for each location $x \in v^q$, the sender makes use of a location-shifting technique $\tau(x)$ that moves x to the closest location y to the border while preserving an equivalent link reception quality. In practice, the sender sets up, for each cell, $x \in v^q$, a relative 2D coordinate system $\{X, Y\}$ having the origin x. The X-axis corresponds to reception quality values. The Y-axis corresponds to cells in transmission range. Let $D(x,y)$ define a distance function, on X-axis, such that $D(x,y) = |Q(x,t) - Q(y,t)|$. Let $C(x,y)$ define a distance function, on Y-axis, such that $C(x,y) = |x-y|$. Let $t_{\overrightarrow{D(x,y)}}$ define a translation operation on X-axis.

$$x \mapsto t_{\overrightarrow{D(x,y)}}(x) = \begin{cases} y & \text{if } \left\| \overrightarrow{D(x,y)} \right\| \leq L_{th} \\ x & \text{else} \end{cases} \tag{24}$$

Specifically, the translation operation $t_{\overrightarrow{D(x,y)}}(x)$ assigns to cell $x \in v^q$ a cell y$\in \overline{v^q}$ having an equivalent link reception quality ($\left\|\overrightarrow{D(x,y)}\right\| \le L_{th}$). In practice, the value of L_{th} is set to 0.01because we are not able to achieve 100% equivalency. Let $t_{\overrightarrow{xy}}$ define a translation operation on Y-axis:

$$t_{\overrightarrow{x,y}}\colon v^q \longrightarrow \overline{v^q} \tag{25}$$

$$t_{\overrightarrow{xy}} = \begin{cases} y & if\ y \ge x \wedge \max_y(C(x,y)) \\ x & \text{else} \end{cases}$$

Specifically, the translation operation $t_{\overrightarrow{xy}}$ assigns to cell $x \in v^q$ a cell y such that y is the closest cell to the border. Finally, the distance shifting technique $\tau(x)$ combines Equation (24) and Equation (25) in order to obtain the final forwarder location $\tau(x)$ defined as follows:

$$\tau(x) = t_{\overrightarrow{xy}} o \left(t_{\overrightarrow{D(x,y)}}(x)\right) = \text{y} \Leftrightarrow \left(\max_{y \in \overline{v^q}}(|x-y|)\right) \wedge \left(\left\|\overrightarrow{D(x,y)}\right\| \le L_{th}\right) \wedge (y \ge x) \tag{26}$$

Let v^F denote the set of resulting forwarders locations. The sender applies a prioritization rule φ_i ($1 \le i \le n_F$) to forwarders locations in v^F . The priorities φ_i are specified in Equation (27).

$$\varphi_i = \varphi\left(v^F(i)\right) = i \tag{27}$$

The locations of forwarders and their priorities φ_i are included in the emergency message. Such an information is useful to coordinate among forwarders in the C-reliability phase.

3.9. C-Reliability

This phase is executed by forwarders of same hop. The forwarders cooperatively perform optimal broadcast repetitions with the objective to reinforce achieving high broadcast reliability. In addition, the forwarders coordinate to select next-hop forwarders. To achieve this, the forwarders take the role of broadcasting the message iteratively with respect to their priorities φ_i. Figure 3.7 shows the state machine of C-Reliability phase. Each forwarder j $(1 \le j \le n_F)$ is assigned a broadcasting timer $\mathrm{T_{ac}}(\mathrm{j})$ and its initial value is indicated in Equation (28). If the broadcasting timer expires, corresponding forwarder j performs $\mathrm{n_{re}}(j)$ repetitions; initial number of repetitions is indicated in Equation (30). Otherwise, the corresponding forwarder is suspended and the value of its broadcasting timer is updated using Equation (29). Similarly, the number of repetitions per forwarder is updated using Equation (31). Initially, highest priority forwarder (with $\max_i \varphi_i$) executes broadcast repetitions (BR) and selects next-hop forwarders while forwarders at lower priorities are suspended. Lower priority forwarders overhear message transmissions and record failed receptions as specified in Equation (31) as long as their broadcasting timer is not expired. Indeed, the repetitions are either successfully transmitted or lost before broadcasting timer of forwarder j expires. If broadcasting timer $T_{ac}(j)$ of forwarder j expires, we distinguish three cases:

(a) Case 1:

Current forwarder j failed to receive all repetitions of higher priority forwarder(s) ($\mathrm{n_{re}}(j) = n_{opt}$). This means that higher priority forwarders are malfunctioning or have moved away. Thus, current forwarder j executes forwarders selection (FS) before broadcasting the repetitions.

(b) Case 2:

Current forwarder j successfully received all repetitions of higher priority forwarders ($\mathrm{n_{re}(j) = 0}$). In this case, current forwarder j remains in idle state and suspends its broadcasting timer.

(c) Case 3:

Current forwarder j didn't receive successfully all repetitions of higher-priority forwarders ($n_F > \mathrm{n_{re}(j)} > 0$). This situation usually occurs when higher-priority forwarders leave the transmission range before accomplishing n_{opt} repetitions. Thus, current forwarder j extracts next-hop forwarders list from the already successfully received repetitions and carries out the rest of repetitions as specified in Equation (31). As long as Equation (33) is not verified, the reliability requirement in current hop is not achieved and the coordination process among forwarders continues.

$$\mathrm{T_{ac}(j) = T_{FS} + n_{opt} * T_{Data}} \tag{28}$$

$$\mathrm{T_{ac}(j) = (j-1) * \Delta s_j} + \mathrm{n}_{re}\mathrm{(j) * T_{Data}} \tag{29}$$

$$\mathrm{n_{re}}(j) = \mathrm{n}_{opt} \tag{30}$$

$$n_{re}(j) = n_{opt} - \left(\sum_{i=3}^{i=j} \left(n_{opt} - \mathrm{n_{re}}(\mathrm{i}-1) \right) \right) \qquad (31)$$

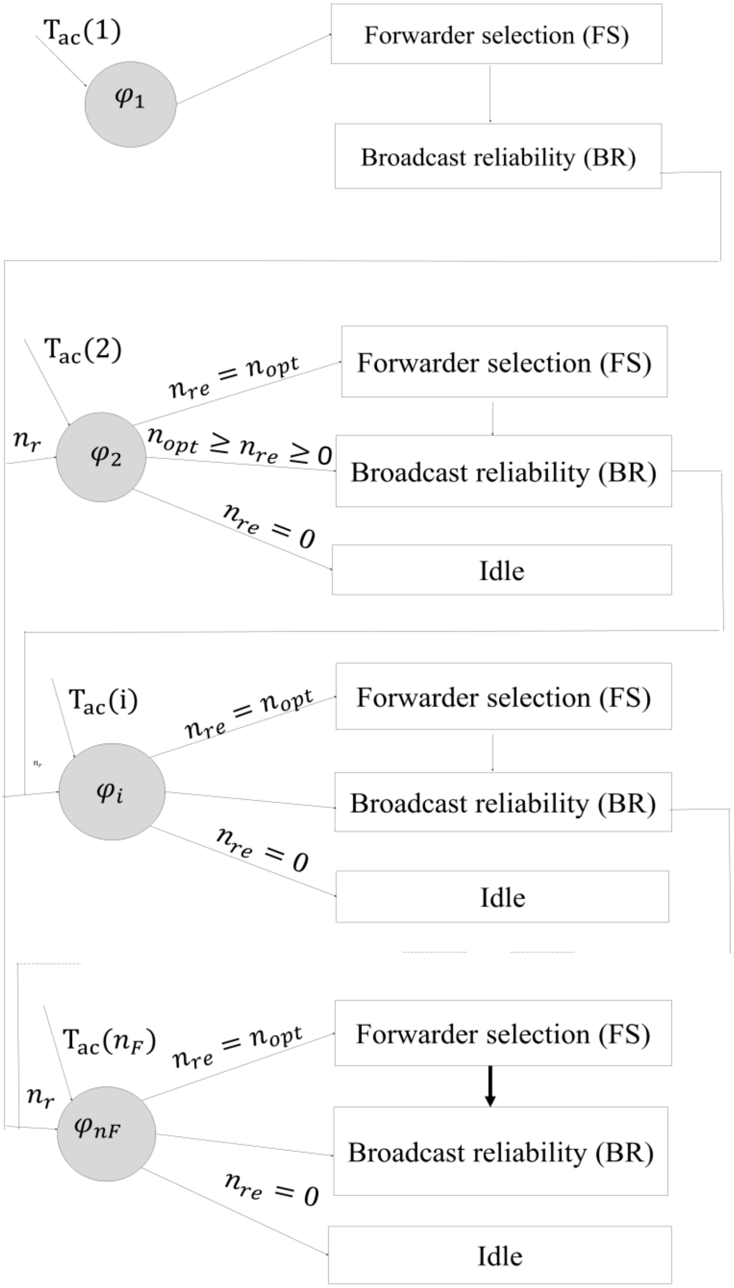


Figure 3.7. State machine diagram of Cooperative reliability

$$\mathrm{T_{ac}(j) = T_{FS} + n_{opt} * T_{Data}} \qquad (28)$$

$$\mathrm{T_{ac}(j) = (j - 1) * \Delta s_j + n}_{re}\mathrm{(j) * T_{Data}} \qquad (29)$$

$$\mathrm{n_{re}}(j) = \mathrm{n}_{opt} \qquad (30)$$

$$n_{re}(j) = n_{opt} - \left(\sum_{i=3}^{i=j}\left(n_{opt} - \mathrm{n_{re}(i-1)}\right)\right) \qquad (31)$$

$$n_{re}(j) = n_{re}(j) + 1 \qquad (32)$$

$$n_{opt} = \left(\sum_{i=1}^{i=j} \mathrm{n_{re}(i)}\right) \qquad (33)$$

3.10. Simulation

In this section, we present a simulation-based evaluation of REMD and 4 other data dissemination schemes (See Table 3.1), i.e., ABSM [42], 3P3B [63], Oppcast [68] and CPF [49]. While [68] and [42] are based on CSMA and propose techniques to improve reliability in multi-hop including intermediate nodes reachability, [49] is a recent repetition-based MAC scheme that uses structured repetitions. We chose also [63] as it is a recent emergency message dissemination scheme.

Table 3.1. Simulated multi-hop broadcast schemes

Scheme	**Number**	**Selection method**	**Reliability**
REMD	multiple	Link recp. qualit.	Fast repetitions
Oppcast [10]	farthest	ACK + farthest	Makeups
ABSM [42]	Backbone	none	ACK in beacons
3P3B[63]	farthest	BRT/CTB	None
CPF [49]	multiple	multiple	POC + Cooperation

A. *Experiment Setup*

We run simulations using Omnet++ 4.3 [101] as a discrete event simulator and Sumo traffic simulator [100]. Our C++ code uses Veins 2.2.1 [102] for DSRC simulated components [102]. We configured Omnet ++ to model the impact of both distance and obstacles (i.e., buildings and moving vehicles) on the signal propagation. In our work, we choose the Rayleigh propagation model to test REMD in a more realistic fading environment. We consider a real city map composed of 3.5 km fragment of a real city street map (www.openstreetmap.org/). Each road segment contains two lanes. We consider the following simulation scenario: a set of vehicles distributed uniformly on road segments (1 vehicle/lane/250m) act as message sources. During simulation, the source vehicles broadcast generic emergency messages at a rate of r messages/s. Simulation results, averaged over 10 runs, are characterized by a 94% confidence interval. Table 3.2 shows the simulation parameters.

Table 3.2. Simulation parameters

Simulation parameter	**Value**
Fading model	Rayleigh [16]
Transmission range (*Tr)*	250 m [27]
WM, Beacon, CP length	292,72, 120
Vehicle density	40-120
Reliability requirement r_{th}	0.99
Simulation duration	150 seconds
Coordinator CP rate, Beacon rate	10 packets/s
Vehicle speed Ve	30-50
Message generation rate	4-5

The performance parameters, we consider in the evaluation of REMD, are: (a) packet reception ratio (PRR) *(%)*: The percentage of vehicles that receive the disseminated message; (b) Average propagation delay *(msec)*: The average length of time between the time a message is transmitted by the source and the time it is received by the vehicles in the target area; and (c) Network load *(Bytes/road segment)*: the amount of traffic in terms of beacons, emergency messages and their retransmissions.

B. Validation

The objective of this section is to validate the analytical findings of REMD using Omnet++ simulations. More specifically, we validate the followings: (a) link reception quality $Q(x, t)$ (Equations (5)-(6)); (b) packet reception rate PRR (Equation (23)); and (c) optimal number of repetitions n_{opt} (Equation (14)).

Figure 3.8 shows link reception quality $Q(x, t)$ plotted against vehicle density. As expected, $Q(x, t)$ decreases when vehicle density increases. This is expected since the traffic of periodic beacons increases with density. This observation validates the use of $Q(x, t)$ to assess 802.11p link reception quality in cells. The analytical results closely follow simulation results especially in the case of high density. The improvement in accuracy, in high density scenarios, is related to the number of received beacons during cell transit time T_s.

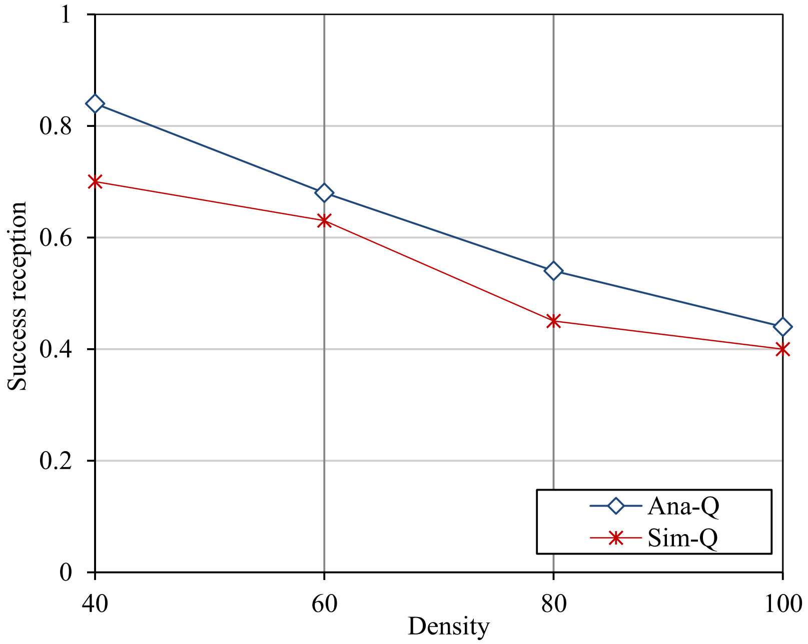


Figure 3.8. Link reception quality vs. Density

Indeed, in high density scenarios, the number of exchanged beacons (during cell transit time T_s) during DCP increases making polynomial modeling based estimation and Curve-fitting [91] in LSP more accurate. Whereas, in low-density scenarios, the number of beacons decreases considerably making polynomial modeling based estimation and Curve-fitting [91] in LSP less accurate. In average, the difference between the analytical and the simulation results is about 3%.

Figure 3.9 shows PRR plotted against the number of repetitions n for three density levels. As expected, we observe that PRR increases with the number of repetitions. This observation validates the basic idea of broadcast repetitions. Again, the analytical results closely follow simulation results especially in moderate to high density scenarios. This behavior can be explained the same way the behavior shown in Figure 3.8, is explained (see previous paragraph). Figure 3.9 shows that the average difference between the analytical and simulation results is below 3%.

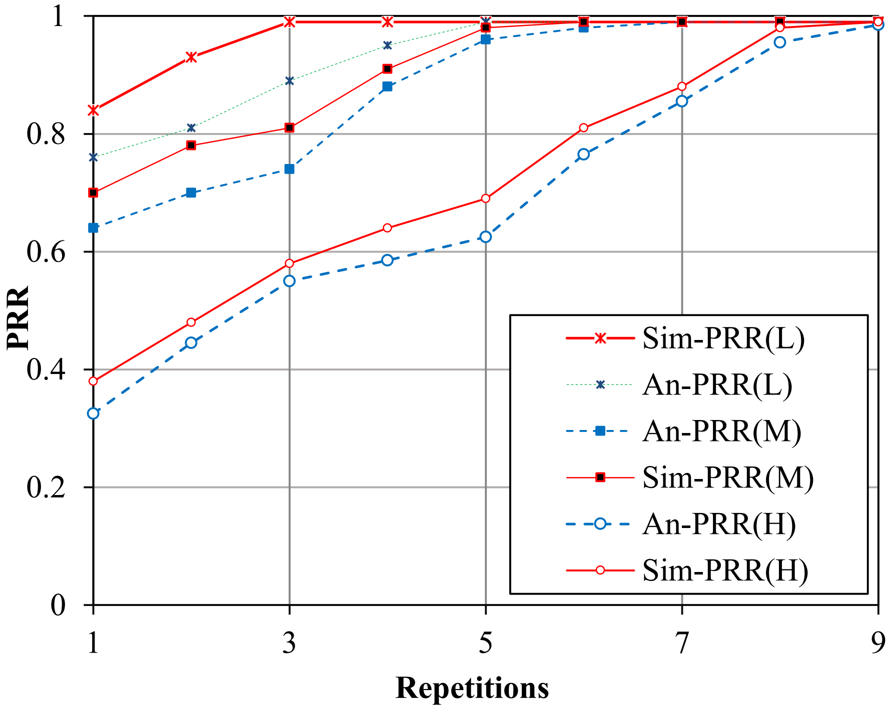


Figure 3.9. PRR vs. Repetitions

Figure 3.10 shows repetitions n_{opt} plotted against density. We observe that the analytical model is very accurate: analytical results practically coincide with the simulation results, in both medium and high density cases. All simulation results in the plot are obtained with 94% confidence interval. Negligible differences, well below 5%, are noted only for low density scenarios.

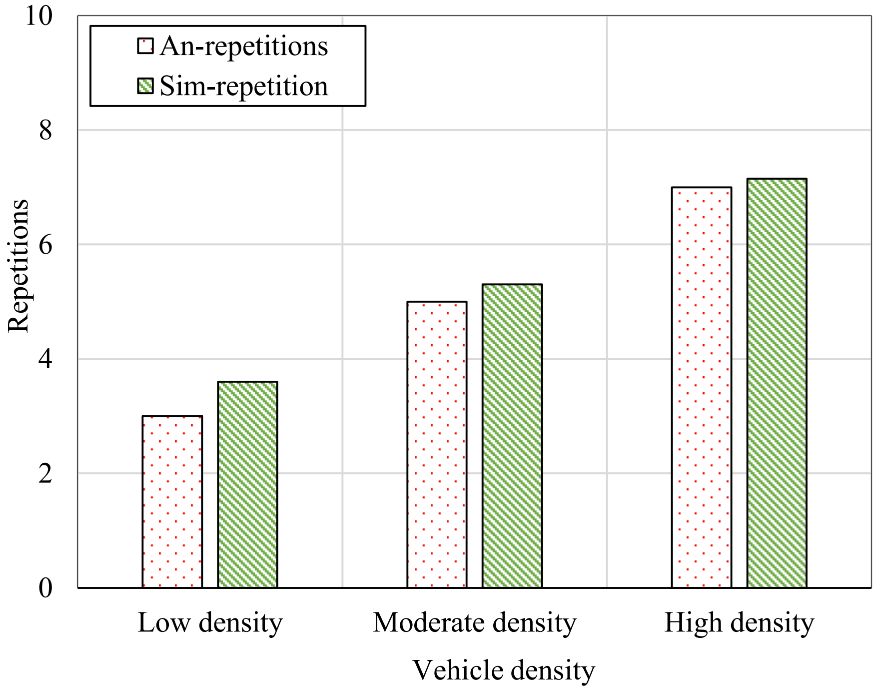


Figure 3.10. Repetitions n_{opt} vs. density

C. Comparison

In this section, we evaluate the performance of REMD for city scenario in terms of PRR, average delay, and network load. The performance results are shown in Figures (3.11)-(3.13).

Figure 3.11 shows the variation of PRR with the vehicle density. Initially, when the density is low, PRR varies between 95% and 99% for all schemes. Then, as the density increases, PRR gradually decreases to 66% for Oppcast, 57% for ABSM, 57% for 3P3B and 62% for CFP. In contrast, we observe that REMD has a constant PRR close to 99% for all densities. The main reason for PRR degradation when using the other schemes is that when vehicle density increases, channel conditions vary (as emulated by the Rayleigh model) resulting in bad link reception quality. In city environment, buildings and moving vehicles impact negatively the reception quality; when coupled with high vehicle density, the situation is much worse. When vehicle density increases, the number of vehicles in the interference range increases. This explains the performance of Oppcast since it does not implement a method to combat hidden terminal problem. In addition, Oppcast selects makeups (forwarders) based on their distance to the sender in order to improve packet reception for intermediate nodes. In high densities, makeups may have low reception quality resulting in packet loss.

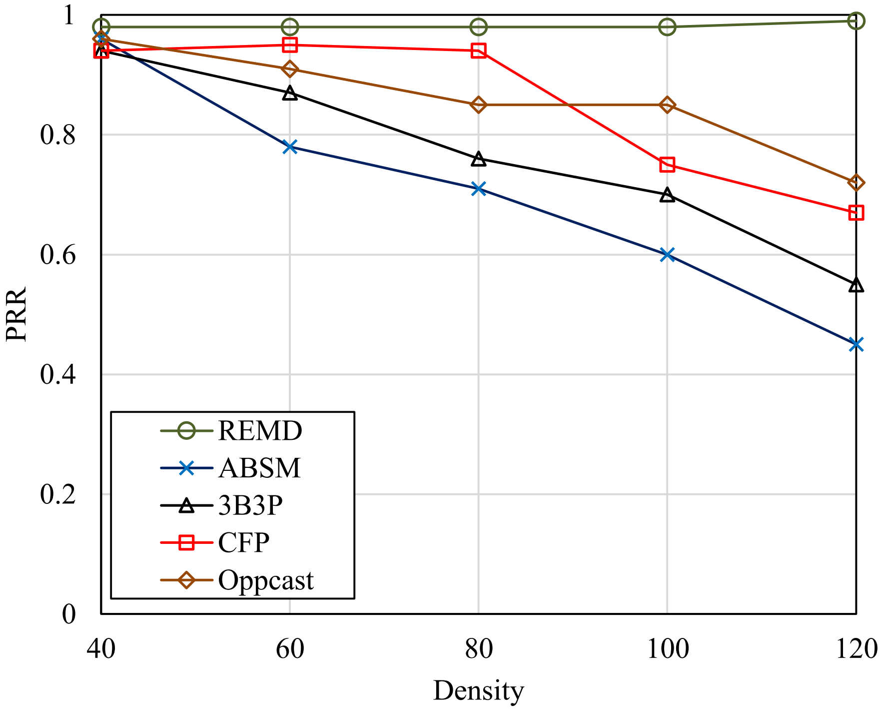


Figure 3.11. PRR vs Vehicle density

In ABSM, beacons include identifiers of the recently received broadcast messages, which serve as acknowledgement of successful message reception. Using this information, backbone nodes can check whether all their neighbors successfully received a message. If this is not the case, a retransmission is scheduled upon the expiration of a timer. The higher the vehicle density, the higher the channel load and the higher the number of incurred collisions. In such a situation, a message may not be delivered to some passing vehicles which may be out of the sender range after the timer expires. In city settings, with high channel loss due to random interference, the resulting backbone links of ABSM are not reliable incurring high packet loss. PRR provided by 3P3B drops when vehicle density goes up. Link loss due to interference with beacons is a major problem. This situation becomes serious when vehicle density increases. Here, the key component (RTB/CTB handshake) in 3B3P is affected. Furthermore, 3P3B selects a remote neighboring node as next-hop forwarder which may move away or be out of range. The poor performance of CFP in city settings in terms of PRR is related to (a) the fixed number of repetitions, where channel loss increases with vehicle density; thus, few repetitions result in unreliability; and (b) the distributed code assignment method: where messages exchanged between vehicles, for code availability information, are vulnerable to packet loss. In such a situation, several nodes may generate same repetition pattern resulting in unreliability. REMD, however, selects forwarders having good link reception quality. In high densities, collision rate and signal power attenuation rate drastically increase. In this case, REMD dynamically predicts/estimates (see DCP and LSP for details) link reception quality in transmission range. Then, REMD carefully fixes the number of broadcast repetitions (in BR) in order to satisfy reliability requirement. Furthermore, REMD combats hidden terminal problem using UPOC.

Figure 3.12 shows average delay plotted against vehicle density.

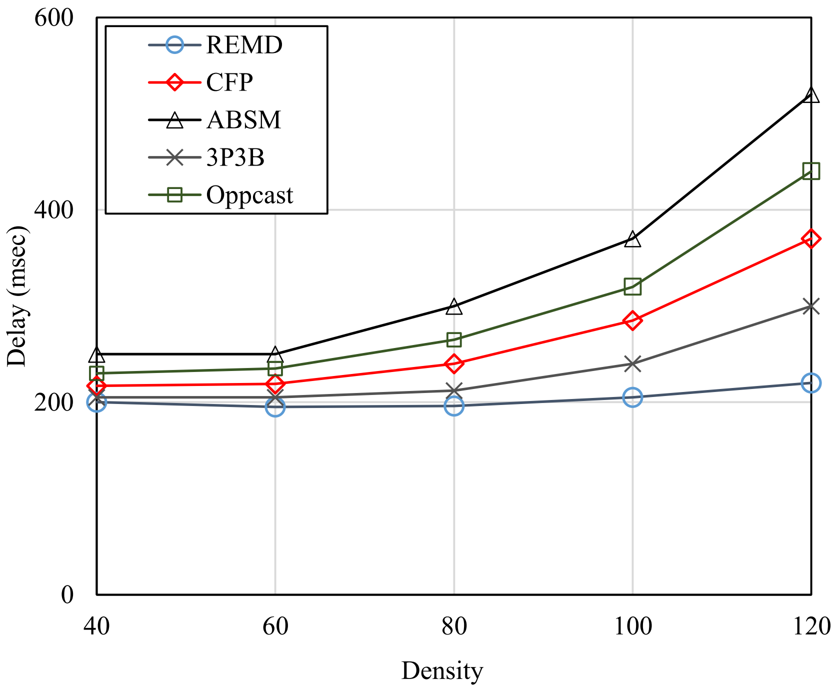


Figure 3.12. Delay vs Vehicle density

We observe that REMD achieves a very reasonable delay when compared to Oppcast and 3P3B. REMD achieves a slightly close delay compared to 3P3B for 40-60 vehicles/km. When vehicle density goes up, we observe that the gap between REMD and 3P3B becomes larger. A possible explanation is that, in dense urban scenarios, data packets may be highly vulnerable to packet loss (i.e., interference). This demonstrates that packet loss due to background traffic (i.e., exchanged beacons) and hidden terminals critically impacts the delay performance of delay-based schemes (e.g., 3P3B). In such a situation, 3P3B performs more retransmissions in order to recover failed receptions. Indeed, exchanged messages are vulnerable to packet loss resulting in higher delay. For all vehicle densities, REMD keeps an average delay smaller than the recommended delay threshold [27]. This is due to the fact that (a) Forwarder selection (FS) phase considers distance to sender in addition to link reception quality; and (b) REMD employs fast repetitions.

Figure 3.13 shows that REMD generates lowest network load. More importantly, the total network load of REMD increases slowly with density. This is because the optimized broadcast repetitions mechanism in REMD avoids redundant rebroadcasting. In opposition, Oppcast and 3P3B continue retransmitting in order to recover failed retransmissions. We conclude that REMD provides the best reliability compared to existing related schemes while, at the same time, provides the best delay which satisfies the requirements of safety applications.

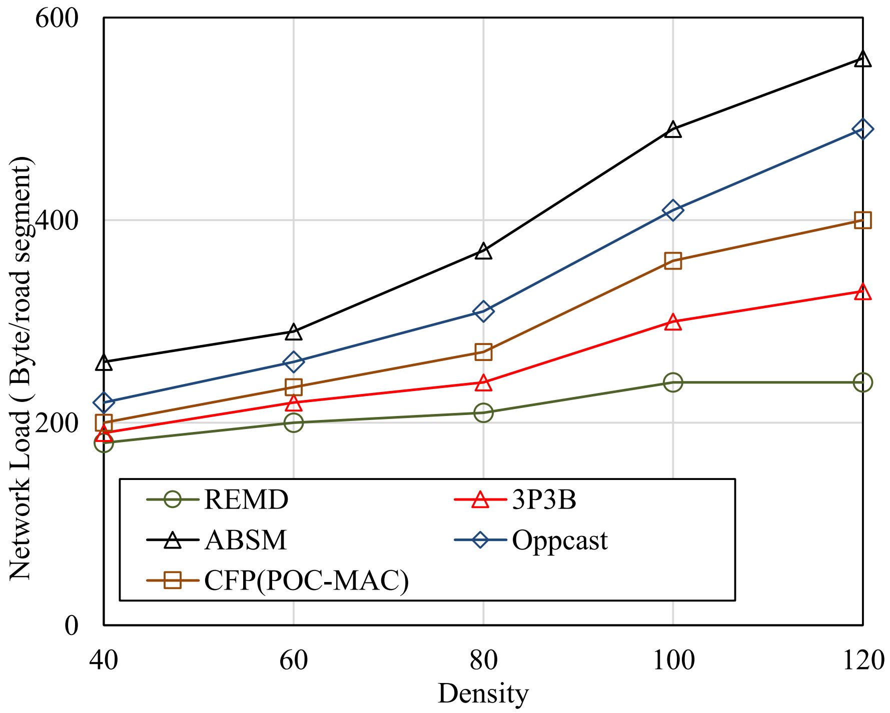


Figure 3.13. Network Load vs Vehicle density

3.11. Conclusion

We proposed REMD as a multi-hop reliable dissemination scheme for urban vehicular networks, compatible with IEEE 802.11p. REMD aims to ensure high broadcast reliability while preserving low end-to-end delay for safety applications. The proposed cell concept provides fine-grained information about wireless channel conditions. By employing curve fitting and polynomial modeling, we are able to predict/estimate an accurate link reception quality in cells. A Max-Min optimisation problem is proposed to compute an optimal number of repetitions while ensuring predefined reliability requirements at each hop. A stochastic modeling approach is used to solve the Max-Min optimization problem. The number of successful receivers is computed from a Poisson Binomial distribution (PBD). FFT enables an exact solution to PBD in $O(n \times log(n)$. To combat hidden terminal problem, Uni-Polar orthogonal codes are applied to the city street network. This paper also proposes a solution for efficient next-hop forwarders selection. REMD selects multiple forwarders with good link reception quality together with their locations at each hop. The forwarders use cooperative transmissions with the objective to achieve high reliability in intermediate hops. Using simulations, we validated the analytical model of REMD. We evaluated, via simulations, the performance of REMD and did show its outperformance compared to existing related schemes. Future work will investigate the use of machine learning tools to improve the estimation accuracy of link reception qualities in different cells of a given zone.

Chapter 4

Bayesian Networks based Reliable Broadcast in Vehicular Networks

Wiem Benrhaiem and Abdelhakim Hafid

Abstract

Reliability is a key requirement of multi-hop safety message broadcasting. DSRC/802.11p MAC layer has strict reliability requirement for ITS safety applications. In city environment, transmission in wireless medium is vulnerable to packet collisions and interferences. Cross channel interference is quite predominant in the presence of high rise buildings and concurrent transmissions. Achieving very high reliability (e.g., 0.99) in the presence of all kinds of wireless network vulnerabilities is a major challenge in urban vehicular networks. This paper proposes a new broadcast scheme, called Bayesian networks and unipolar orthogonal Code based Reliable multi-hop Broadcast (BCRB) to address this issue. Our objective is to guarantee strict reliability requirement (e.g., 99%) in each hop using broadcast repetitions. We propose an approach, based on using Bayesian networks, that exploits periodic exchanged beacons to accurately infer 802.11p link reception quality at each hop. Using this information, a sender determines an optimal number of broadcast repetitions, multiple forwarders and their positions. To combat interference, during broadcast repetitions, we make use of Uni-Polar Orthogonal Codes (UPOC). For multi-hop transmissions, multiple forwarders cooperatively communicate at each hop with the objective to achieve high broadcast reliability in next hop. Simulation results show that BCRB achieves very high reliability in lossy wireless channel. Furthermore, BCRB satisfies transmission latency requirements for time-sensitive vehicular applications with relatively low overhead.

Key words: Broadcast Reliability, Bayesian Network, Uni-Polar Orthogonal Codes, Urban vehicular network, stochastic modeling.

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4.1. Introduction

The successful dissemination of emergency messages makes a difference between life and death. Broadcast-based message dissemination needs timely and lossless medium access. In big cities, several emergency events have to coexist together to achieve life-saving goals. On detecting an unexpected event (e.g., a traffic accident), a vehicle immediately issues an event-driven message to notify nearby related drivers ahead of time to allow them to take action in time. Conceived to be just up to few hundred meters [27], an emergency message has to be forwarded hop by hop to far away drivers. Figure 4.1 shows a scenario of hazardous driving conditions on adjacent road segments. Car *A* (involved in a crash) broadcasts an emergency message M_A to the vehicles in the risk zone of *A*. Car B (involved in a crash) broadcasts an emergency message M_B to the vehicles in the risk zone of B. On receiving a message, a vehicle can slow down/brake to avoid hitting the car(s) it follows.

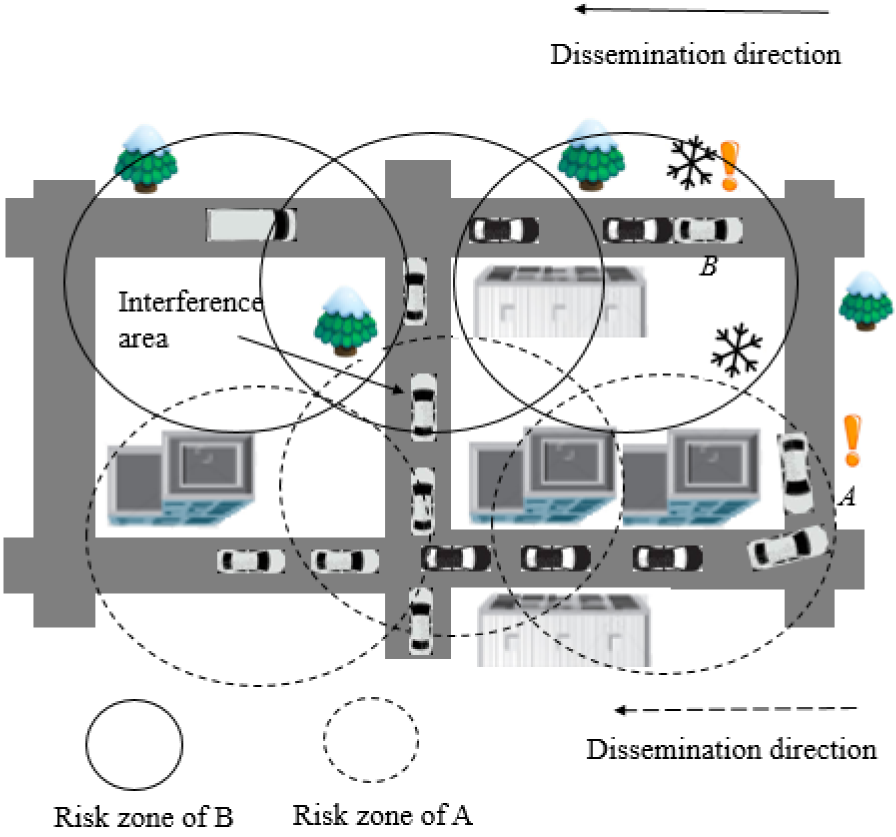


Figure 4.1. Illustration of multiuser interfering nodes

A single uninformed vehicle, may result in terrible causalities [27][28][29][30]. Thus, no driver should be deprived of information about emergency events. Consequently, high reliability of message dissemination is required (e.g., the probability of packet reception should be greater than 0.99 [27]). In vehicular networks, the nodes share a common wireless channel by using the same radio frequencies. Each node competes for channel access when it needs to transmit, without any guarantee of success.

Typically, several factors reduce probability of successful message reception in wireless communications. Random loss is caused by lossy wireless channels and node mobility. In city road networks, severity of interfering nodes increases (i.e., overhearing a packet not intended for the receiving node is considered as interference) [29][30]. Vehicles may receive signals from other vehicles on adjacent streets. Both periodic messages (i.e., beacons) and event-driven messages [30] are transmitted on the same control channel (CCH) of DSRC. Periodic exchanged beacons increase severity of interfered/collided packets. Furthermore, high mobility of vehicles makes reliability of communication in vehicular networks more complex [27]. Despite DSRC/802.11p based broadcast has the potential to provide low latency in one-hop [28], it is reported to be defective in terms of reliability making it a major reason that hinders the deployment of IEEE DSRC/802.11p [32][37]. IEEE DSRC/802.11p defines the MAC layer to be based on CSMA/CA [32] with minor modifications. The channel access mechanism of DSRC/80211p is Enhanced Distributed Channel Access (EDCA); it is not able to provide predictable reliability for safety services. As a result, IEEE DSRC/802.11p MAC is not able to guarantee broadcast reliability. More specifically, 802.11p MAC does not implement any broadcast reliability mechanism [33] (e.g., DSRC/802.11p-based broadcast does not support acknowledgement [32]). Comparing broadcast to unicast, no mechanism is used to alleviate the hidden terminal problem (e.g., virtual carrier sensing is not used in IEEE 802.11 broadcast [32]). In multi-hop broadcasting, forwarder selection increases the probability of collisions/interference [28][33]. IEEE 802.11 MAC does not offer any specific support to improve reliability in multi-hop, apart from the naïve flooding scheme [38]. However, such a solution may lead to the broadcast storm problem [39] resulting in unreliability (i.e., high packet loss) and delayed communication [39].

Several CSMA-based multi-hop broadcast schemes have been proposed (e.g., [38][60][33]). The main idea is to use control packet exchange [64] and/or acknowledgement packet [64]; and to select a single forwarding node at each hop. DSRC/802.11p-MAC [32] can't characterize/detect random access events resulting in unreliability. In harsh network conditions, a sender does not know whether its transmitted message is successfully received or not. Furthermore, in case the forwarder has moved away or is malfunctioning, the multi-hop communication would not be possible.

Recently, repetition-based broadcast MAC schemes [46] [48] have been proposed to enhance broadcast reliability for safety applications. The basic idea is to repeat (i.e., transmit) the message multiple times within a frame in order to increase reception probability; a frame consists of L time slots. Random repetitions schemes like SFR [46] and AFR [46] randomly select repetition slots. It has been proved that selecting k slots out of L raises the probability of successful message reception [46]. Expanding upon this finding, structured repetitions are proposed to further protect repeated packets from hidden terminal problem [49]. Positive Orthogonal Codes (POC), known as Uni-Polar orthogonal codes (UPOC) [47], as structured repetition patterns, have been reported to suppress hidden terminal problem [49]; an UPOC is a binary code of fixed length L , where cross-correlation between any pair of code-words is less than a given value [49]. However, without evaluating the channel condition, if fixed number of messages is forwarded within frame, we may be sending either too few or too many packets. Too many packets may lead to considerable overhead and too few packets may lead to unreliability. It is important to note that most existing repetition-based MAC schemes [72][73] are not compatible with emerging DSRC/802.11p [32].

In this paper, we propose a novel reliable multi-hop broadcast-based MAC scheme, called BCRB, compatible with emerging IEEE DSRC/802.11p. The key contributions of this paper can be summarized as follows:

(1) Propose a Bayesian networks based scheme to estimate, with good accuracy, link reception quality, at different locations in the zone covered by the transmission range of the sender; this estimation is based on beacons periodically generated by vehicles.

(2) Propose a Max-Min optimization problem, together with its resolution, that allows to determine an optimal number of repetitions (i.e., message transmission) to satisfy 1-hop reliability requirements. The input to this optimization problem is link reception qualities computed in (1).

(3) Propose an UPOC-based scheme that carefully generates repetition patterns to minimize/avoid interferences between senders (vehicles) located on different road segments.

(4) Propose a scheme that selects appropriate forwarders, at each hop, with the objective to satisfy multi-hop reliability requirements; these forwarders, at each hop, cooperatively repeat the message (based on the number of repetitions computed in (2) and repetition patterns determined in (3)) to support reliability requirements in next hop. They cooperatively repeat the message an optimal number of times with the goal to ensure high reliability in next hop.

The remainder of this paper is organized as follows. Section 4.2 presents related work. Section 4.3 briefly overviews BCRB. Sections 4.4-4.9 presents the components of BCRB. Section 4.10 evaluates, via simulations, the performance of BCRB. Finally, section 4.11 concludes the paper.

4.2. Related work and Motivation

In this section, we briefly review existing CSMA-based broadcast medium access control (MAC) schemes. Then, we present repetition-based broadcast medium access control (MAC) schemes.

A. CSMA-based broadcast

Several multi-hop broadcasting schemes have been proposed. They can be classified into 3 broad categories: Probabilistic schemes (e.g., [37], [58]), Backbone-based schemes (e.g., [59][44]) and Delay-based schemes (e.g., [60][33][34][61][62][63][64])

Probabilistic schemes are designed to alleviate broadcast storm problem. The main idea is to reduce the percentage of redundant messages by selecting only some vehicles to rebroadcast messages. SAPF [37] determines broadcast probability based on vehicles speed. Weighted p-persistence [58], slotted 1-persistence [58], and slotted p-persistence [58] are the first proposed broadcasting schemes. However, such schemes for multi-hop broadcasting don’t consider wireless signal propagation issues (i.e., severe multi-path fading and shadowing). In high lossy channels, such schemes generate redundant retransmissions and incur a large communication delay. This makes them not suitable for safe driving in dense urban areas. Furthermore, these contributions don’t consider MAC layer issues, such as interference management and random access. Thus, broadcast over lossy wireless links remains unreliable.

Backbone-based schemes are designed to disseminate messages based on already formed virtual backbone structures [65]. DBA-MAC [44] selects backbone nodes based on estimated lifetime of wireless links. In city setting, links of the backbone nodes are vulnerable to failure resulting in high communication overhead (creation and maintenance of backbone structure). Surrounding buildings and mobility of nodes impact quality of wireless links resulting in week connectivity between backbone nodes. Intermediate nodes are the vehicles located in the area between two successive backbone nodes. ABSM [59] includes message identifier in beacons to serve as acknowledgements. If an acknowledgement is not received from an intermediate node, the backbone node rebroadcasts the message. The presence of obstacles may cause massive beacon losses. In this context, ABSM [59] performs redundant retransmissions.

Delay-based schemes are designed to select the farthest neighboring node as the next relaying node in order to reduce hop count. UMB [60] and BPAB [33] divide the transmission range into several sectors. The vehicle that is located in the farthest sector is elected to forward the message. UMBP [64] makes use of black-burst and asynchronous contention among remote neighboring nodes to select a farthest node. 3P3B [63] allows the farthest possible vehicle in the farthest sector from the sender node to perform forwarding. In PAB [34], each node receiving a packet determines the distance with respect to the sender. Then, it picks a waiting time inversely proportional to the distance from the sender to the receiver. The farthest node is whose timer expires first. PMBP [61] and ROFF [62] select the farthest forwarding node according to its distance to the sender. It is a known fact that the sender is aware of the topology change through received beacons. The time gap between beacon sending time of a neighboring node and the time at which that node becomes a forwarder may be very long. In such a situation, the farthest node may not be within the range of the sender resulting in unreliability. Besides, one-hop broadcast reception rate is lower in farthest positions due to channel fading. As a result, the farthest node may not receive the message and the sender will remain unaware of failed reception. To overcome such limitations, several contributions (e.g., [60][62][63]) propose to use a handshake mechanism with the goal to decrease the impact of hidden terminal problem and/or to transmit acknowledgements (ACKs). To combat hidden terminal problem, schemes in [60][67] use request-to-send/clear-to-send (RTS/CTS) mechanism before transmitting a data packet. UMB [60] uses RTS/CTS handshake with only one of the recipients among sender’s neighbors. CLBP [67] exchanges BRTS/BCTS packets (Broadcast RTS/CTS inspired by the RTS/CTS mechanism in IEEE802.11) before sending data packet. BPAP [33] relies on a control message exchange similar to RTS/CTS handshake to overcome the hidden terminal problem. 3P3B [63] adopts

RTB/CTB handshake to cope with the hidden terminal problem in multi-hop wireless networks. In city settings, control packets may be potentially lost because the length of safety messages is short and comparable to that of RTS control packets [64]. Therefore, the probability of collision for RTS packets is not negligible. Even if RTS/CTS handshake protects transmission of emergency messages when multiple interfering nodes coexist, it can't protect from shadow and fading effects due to obstacles. Oppcast [68] and EMDOR [69] use explicit broadcast acknowledgements (ACKs) to select forwarders. However, acknowledgement-based mechanisms are generally not robust under harsh channel conditions. More specifically, ACK messages are prone to interference. In city settings, the above schemes perform multiple retransmissions that may lead to the violation of delay requirements for safety applications.

With respect to the reachability of intermediate nodes, few schemes propose methods to ensure successful packet reception for intermediate nodes:

(a) Schemes in [60][63][67] perform message "overhearing"; if the farthest node is successfully selected, then the other nodes in between (i.e., intermediate nodes) can overhear the source transmissions [70]. In lossy channel, transmissions are vulnerable to interference/collisions. Here, an intermediate node may not receive the message;

(b) Scheme in [69] performs ACK-overhearing. After transmitting the message, the forwarder sends an ACK to the sender. If an intermediate node overhears an ACK but it didn't receive the corresponding message, it requests the sender to perform rebroadcasting. In the case of multiple nodes not receiving the message, the sender has to do multiple retransmissions that may lead to low packet reception rate (e.g., because of collisions). Hence, ''Overhearing'' does not guarantee successful message reception; and

(c) Scheme in [68] elects intermediate forwarders "makeups" at each hop to enhance one-hop reliability. The makeups perform rebroadcasting to enhance packet reception rate (PRR). However, the 'makeups' are selected, based on their distance to the sender. In adverse network settings, selected makeups may have low link reception quality resulting in a non-guaranteed reliability for intermediate nodes.

To conclude, conventional DSRC/802.11p-based MAC broadcast schemes are defective in terms of reliability.

B. Repetition-based MAC schemes

The objective of message repetition [46] is to meet one-hop requirements in terms of reliability and latency [46]. The basic idea is to divide time into frames of fixed size. A frame of L slots (equal to the message lifetime) is allocated to each vehicle intending to transmit an emergency message. Slot length equals to the transmission time of a single packet [105]. A vehicle is allowed to repeat the message multiple times within a frame. The intuition is repeating the message more than once raises probability of reception. Message repetition schemes can be divided into two broad categories:

(a) Random repetitions [46][48], where the repetition pattern (timeslots in which a node is allowed to transmit in a frame) is chosen randomly. SPR [46] transmits the message in each timeslot with probability p and remains idle with probability $1 - p$. In this approach a packet may be transmitted L times or not transmitted at all. SFR [46] randomly chooses k slots out of the L slots. It is proved in [46] that SFR is better than SPR and IEEE 802.11a in terms of reliability. FR-EMD [71] extends SFR to multi-hop and adjusts the number of repetitions according to vehicle density. However, it does not take into account signal propagation issues (e.g., slow-fading and shadowing) caused by obstacles. RB-CD [48] focuses on reliable broadcasting for emergency messages. The computation of the number of repetitions does not consider channel conditions. Furthermore, RB-CD [48] does not combat hidden terminal problem. In situations where a large number of transmissions happen, random access results in high packet loss rate. This is because randomly choosing transmission slots incurs collisions/interference; and

(b) Structured repetitions [72][73][49], where the transmission slots are obtained based on unipolar orthogonal codes. It is shown in [72] that transmission/repetition patterns obtained from Optical Orthogonal codes [47] perform better than SPR [46] and SFR [46] in terms of probability of transmission success and delay. Unipolar orthogonal codes [47] represent binary sequences $\{0,1\}$ with small cross-correlation. Obtaining repetition patterns from these codes guarantees that maximum number of times that two vehicles simultaneously transmit is less than the cross-correlation. Schemes in [72][73] focus on broadcast reliability of periodic beacon messages using Unipolar Orthogonal Codes. The scheme in [72] does not account for fast moving vehicles and highly dynamic wireless channel. In POC-MAC [73], repetition patterns distribution uses considerable channel resources (i.e., available codes are acquired through message-passing) in high density network. In lossy channel, the exchanged messages (message-passing between vehicles to update codes availability information) can be lost. This results in erroneous code assignment (i.e., two neighboring nodes may allocate same code) resulting in unreliability. Furthermore, the authors compute the probability of transmission success without taking into account signal propagation issues. In addition, repetition-based MAC schemes [72][73] are not compatible with emerging DSRC/802.11p [32]. CPF [49] extends POC-MAC [73] for multi-hop emergency message dissemination in highway scenarios. In lossy wireless channel, selected forwarders may have bad link reception quality resulting in failed receptions; whatever the number of repetitions, if a forwarder position is exposed to shadowing and multipath effects, the message dissemination may fail resulting in unreliability. CPF does not guarantee high broadcast reliability in lossy channel. Indeed, if fixed number of message repetitions is forwarded over a frame, they may be sending either too few or too many packets. Too many packets lead to message overhead resulting in collisions and too few packets lead to unreliability. Hence, an optimal number of repetitions must be determined according to channel conditions. In a previous work, we proposed REMD [106] which uses structured repetitions to ensure high broadcast reliability. It computes an optimal number of repetitions based on an estimation of link reception quality in different locations (called also cells) in the transmission range of the sender. REMD proposes an analytical model to estimate link reception quality. However, it makes the assumption that link reception qualities of adjacent cells are independent which is not realistic in real-life scenarios.

In this paper, we propose BCRB that uses a machine learning-based approach to estimate link reception quality at different locations in the zone covered by the transmission range of the sender; BCRB does not make any assumption about the link reception qualities of adjacent nodes. The goal of this paper is to develop an efficient scheme, compatible with DSRC/80211p-based MAC that makes use of UPOC and message repetition, while taking into account real-time channel conditions, for reliable multi-hop communication in urban scenarios. In the following sections, we will present the details of this scheme.

4.3. BCRB: An Overview

The objective of BCRB is to disseminate emergency messages with very high reliability (e.g., r_{th}=99%)) [107] in vehicular networks. The basic idea, behind BCRB, is to transmit/repeat the message multiple times. BCRB uses transmission/repetition patterns based on Uni-Polar Orthogonal Codes (UPOC) to combat interference. In order to compute an optimal number of repetitions, to satisfy reliability requirements, it predicts with high accuracy, using Bayesian networks, link reception quality in transmission range of the sender. It also uses this information to determine the number of forwarders, together with their positions, that will perform the repetitions. Indeed, these forwarders cooperate to satisfy reliability requirements.

A. Assumptions

In this paper, we consider a scenario where vehicles are moving on urban streets. We assume that (1) Vehicles are equipped with a Global Positioning System (GPS) and digital road maps; (2) All vehicles are equipped with IEEE 802.11p wireless technology and high computation capabilities; (3) Vehicles exchange periodic beacons; (4) Obstacles (e.g., buildings) exist; thus, this may impact communication among vehicles; (5) Vehicles, that detect emergency situations, are distributed randomly with predefined density; and (6) Emergency message transmission duration is one timeslot.

B. System model

The network model consists of a grid-like city streets plan. The length of a segment (the area between two road intersections) is the same as the transmission range of vehicles [108]. Figure 4.2 shows that each lane, in a segment, is divided into cells with predefined length (e.g., length of a Car = ~ 6 meters). Thus, a cell represents a possible vehicle location. We define transit-time T_s as the cell transit time by a vehicle. In a cell, during T_s, for each beacon interval, moving vehicles are assumed to occupy a single cell. Each possible vehicle position is assigned a cell number. The transit time T_s is computed as follows: $T_s = \frac{y}{V}$, where y is the cell length and V is the vehicle average speed in urban scenario (i.e., $V = 50$ km/h [51]). Generally, transit delay is multiple times the length of beacon interval T_b (e.g., T_b=0.1 sec [30][2]).

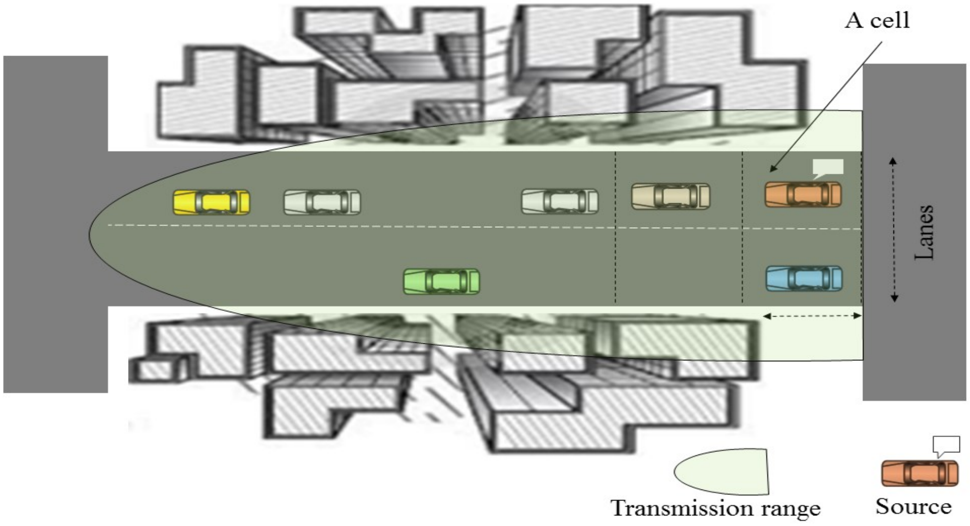


Figure 4.2. Road segment structure

C. Definitions

In the following, we present definitions of relevant terms used to describe BCRB.

- **Source node:** It defines the vehicle that detects an emergency event.
- **Regular vehicle:** It defines a passing vehicle. During beacon interval, such a vehicle records cell information (beacons reception state). Then, it includes this information in its next beacon. We use the term regular vehicle or vehicle interchangeably to denote a passing vehicle.
- **Coordinator:** It defines a vehicle located around the center of a road segment that processes received beacons of vehicles in the effective road segment (i.e., the current road segment). There exists a coordinator per road segment.
- **Coordination Packet (CP):** It defines a packet transmitted periodically by coordinator. Coordinator transmits periodic CPs instead of periodic beacons. CP includes the status information of coordinator (e.g., position, velocity, direction, etc.) together with additional information (see Section 4.5 for details). The transmission power of CP is two times the beacon's one.
- **Sender:** It defines the current broadcast node (a node that intends to transmit the emergency message). The source is a sender when it first broadcasts the emergency message.

- **Target area:** It defines the geographical area that includes all vehicles approaching/driving, towards the source, that are intended recipients of the emergency message generated by the source node.
- **Uni-Polar Orthogonal Codes** (UPOC) [47]: It defines a group of (0, 1) sequence with good cross-correlation property (i.e, Cross-correlation is a measure of similarity of two (0, 1) sequences).

D. Overview

The goal of BCRB is to determine optimal number of message repetitions and multiple forwarders and their positions in order to satisfy reliability requirement at each hop. BCRB consists of an initialization phase, called Interference Suppression (I-Suppression), and 5 key phases: (1) Training data collection (TDC); (2) Graphical model learning (GML); (3) Broadcast Reliability (BR); (4) Forwarders selection (FS); and (5) Cooperative reliability (C-reliability). I-Suppression is executed once to assign, for each road segment, a Uni-polar orthogonal code (UPOC) while ensuring zero-correlation between adjacent road segments. TDC and GML run continuously whereas BR, FS and C-reliability run only when an event requiring an emergency message to be disseminated to vehicles in a target area occurs. It is worth noting that BCRB is also applicable for safety applications that rely on one-hop message broadcast. In this context, FS and C-reliability phases are omitted.

(1) **TDC:** It is executed by regular vehicles and coordinator of same road segment. More specifically, a vehicle passing a cell collects reception-state (i.e., beacon reception is successful or not) information of that cell. Then, it includes this information in its next beacon. Coordinator processes received beacons with the objective to form training database.

(2) **GML:** It is executed by coordinator. Coordinator exploits training database to estimate link reception quality of 802.11p wireless link in cells; then, it includes this information in next CP.

(3) **BR:** It is executed by the source and forwarders. Using recent received CPs, the source (or the forwarders) computes optimal number of broadcast repetitions that satisfy reliability requirements in its transmission range.

(4) **FS:** It is executed by the source and a specific forwarder. Using recent received CPs, the source (or the forwarder) selects multiple forwarding nodes and their positions in transmission range.

(5) **C-Reliability:** It is executed by forwarders of same hop, in a distributed fashion. The forwarders coordinate their transmission timers to perform cooperative communication. They select next-hop forwarders and send/repeat the emergency message an optimal number of times with the objective to satisfy reliability requirements in next hop.

4.4. Training Data Collection: TDC

TDC enables collecting instantaneous reception-state (i.e., beacon reception is successful or not) information in transmission range. TDC is executed by regular vehicles and coordinator of same road segment. Coordinator is selected dynamically through exchange of beacons (details of the selection process can be found in [31]). At any time, there is only one coordinator per road segment. Vehicles exchange periodic beacons with each other via control channel. A vehicle passing a cell c receives beacons from other vehicles in the same road segment. A vehicle remains in same cell c for a number of successive beacon intervals (e.g., this number is 4 if speed is 50 km/h, cell length is 6 meters and beacon period T_b=0.1 [30][2]). During beacon interval, a vehicle transiting cell c records position information (cell number) and fills a reception-state array $A = (a(1), a(i), \dots, a(N))$ where N is equal to the number of cells in road segment and $a(i)$ is a binary variable that indicates whether or not a beacon is successfully received from cell i in same road segment. If successful, $a(i)$ assumes 1; otherwise, it assumes 0 (See Figure 4.3). Note that the receiver is not able to differentiate between failed receptions and non-occupied cells. At end of beacon interval, the vehicle includes the sequence of bits $a(i)$ in its next beacon. Coordinator is in charge of processing beacons received from vehicles in its road segment. It extracts binary sequences from received beacons into N x N matrix structure.

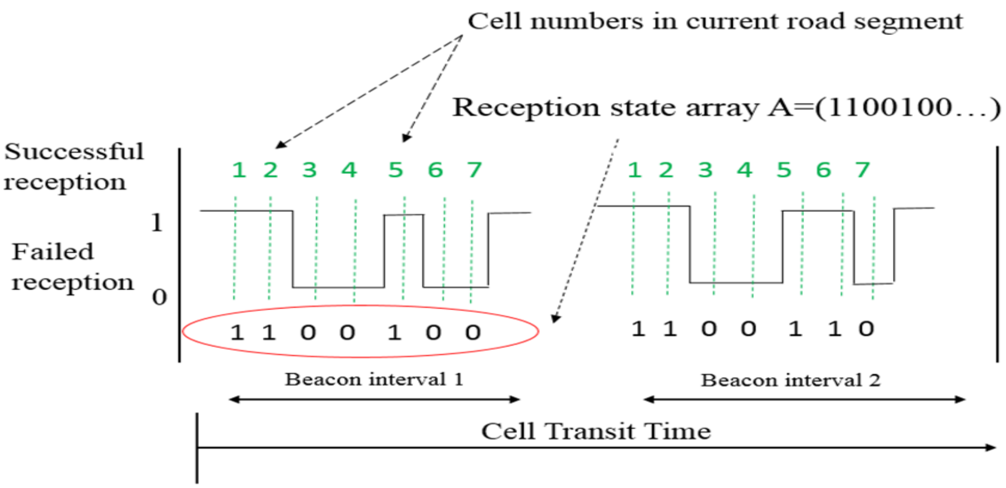


Figure 4.3. Cell information (i.e., Beacons reception state) collection during cell transit time.

Figure 4.4 shows an N x N matrix where a row represents beacons reception state in a cell. The row entry corresponding to the cell number is marked as a non-observed variable.

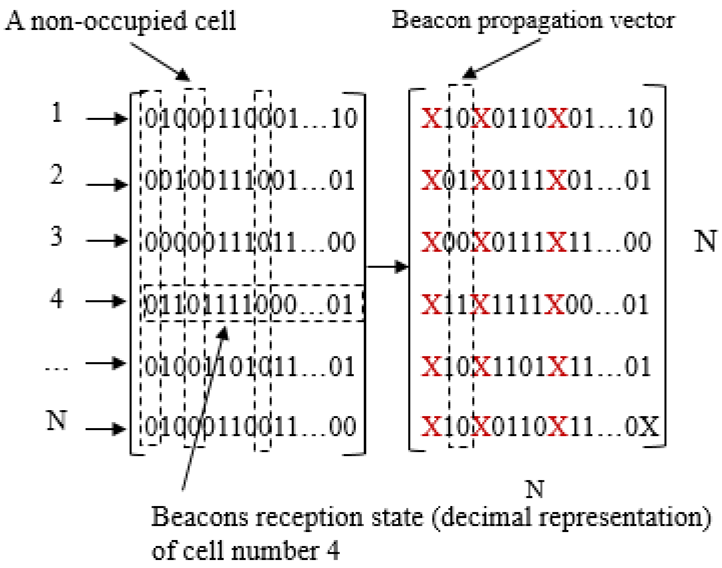


Figure 4.4. N x N matrix

Hence, all diagonal elements of the N x N matrix are marked as non-observed variables. A column of the N x N matrix determines reception information (0 or 1) corresponding to a specific broadcasted beacon; a column with only zero entries represents a non-occupied cell. Coordinator marks entries of rows corresponding to non-occupied cells as non-observed variables. Note that entries of a row/column corresponding to a non-occupied cell are marked with the symbol x to indicate a non-observed variable. Then, the matrix entries (i.e., observed ones) are included in the training data. A row of the N x N matrix represents a training sample. Each beacon period, there are $Ng \leq N$ observed variables (training samples) added to the training data. Size of training data (in terms of number of observed variables) depends on both TDC phase duration and nodes density. Coordinator uses the training data to train a Bayesian Network in GML phase.

4.5. Graphical Model Learning: GML

Coordinator, of a road segment, executes GML to estimate link reception quality in transmission range using Bayesian networks. A Bayesian network is a directed, acyclic graph that discovers and represents dependencies, among random variables from observational data [110]. It represents the causal relationships between uncertain events. Using this property, coordinator predicts/estimates the 802.11p link reception quality in each cell. The 802.11p link reception quality can't be predicted/estimated with total certainty. Using probability, coordinator can estimate how likely message reception event is to happen. Bayes' Theorem is used to quantify uncertainty [110]. Indeed, by hypothesizing that link reception quality in a cell is good (i.e., successful packet reception), the theorem defines a rule for refining such a hypothesis; It factors an additional evidence E (an observed data) and a background information θ (a prior knowledge). The result represents the probability that the hypothesis is true:

$$\mathrm{p}(\mathrm{E}|\theta) = \frac{\mathrm{p}(\theta|\mathrm{E}) \times \mathrm{p}(\theta)}{\mathrm{p}(\mathrm{E})} \tag{1}$$

Let N be the number of cells in transmission range, and $X_i \in \psi \ (0 \leq i \leq N)$ be a random variable associated with cell i (a possible receiver i) assuming 0 or 1. For each random variable X_i, coordinator has to compute the probabilities $p(X_i = 1)$ and $p(X_i = 0)$. Let X_i be a Bernoulli random variable $X_i \sim \beta(p_i(x))$ with reception probability $p_i \in \zeta$; in this paper, we consider that reception probability $p_i = p(X_i = 1)$, is the 802.11p wireless link reception quality in cell i. Coordinator explores the possibility of causal relationships between adjacent cells , using Bayesian network, in order to accurately estimate/predict reception probability p_i. To build

Bayesian network, in current road segment, coordinator learns causal relationships (i.e., the graph structure) and the probabilities (i.e., parameters) from training data (i.e., output of TDC). Let $\mathcal{g}(\psi, \zeta)$ denote Bayesian network (a graph and its associated parameters), where ψ represents the set of random variables and ζ represents conditional probability tables. Coordinator determines joint probability distribution of link reception qualities; it can be expressed as follows;

$$\mathrm{P}(\mathrm{X}_1, \mathrm{X}_2, \dots, \mathrm{X}_\mathrm{N}) = \prod_{\mathrm{k}=1}^{\mathrm{k}=\mathrm{N}} \mathrm{p}(\mathrm{X}_\mathrm{k} | \mathrm{pa}(\mathrm{X}_\mathrm{k})) \tag{2}$$

where $\mathrm{p}(\mathrm{X}_\mathrm{k}|\mathrm{pa}(\mathrm{X}_\mathrm{k}))$ is the local conditional probability distribution associated with receiver k and $\mathrm{pa}(\mathrm{X}_\mathrm{k})$is the set of indices labeling the parents of node k; $\mathrm{pa}(\mathrm{X}_\mathrm{k})$ can be empty if node k has no parent [40].

- Learning graph structure

In this paper, we use a constraint-based search technique, namely the widely used PC (Peter-Clark) [111], which searches through possible graph structures to learn the graph structure. PC consists of three main steps: (a) Construct a non-direct graph using conditional independence and independence tests; (b) Determine V-structures (Note that a V-structure is an ordered tuple (X,Y,Z) such that there is an arc from X to Y and from Z to Y, but no arc between X and Z); and (c) Propagate direction of some arcs. It starts with an initial completed graph structure. Then, it performs the three steps to find out relations among nodes using both independence tests and conditional independence tests [112]. In this paper, we propose a modified version of PC algorithm, called V-PC, adapted to vehicular network.

(a) Initial graph structure

In vehicular networks, starting from a complete graph results in an exhaustive search in the space of possible graph structures which is not practical. For three lanes road segment, we have 50 cells per lane and 150 cells per road segment. Hence, there is $|\psi| = 150$ random variables to model links reception quality in the road segment. The total number of graph structures is huge. Furthermore, even though direct or indirect relations among all random variables (cells) in transmission range exist, it is very difficult to directly describe the causality relationship between all cells. The search algorithm has to determine causality relationships between too many variables. To overcome this, we assume that any cell is conditionally independent of its non-adjacent cells given its adjacent cells, i.e., there is no direct influence between a cell and its non-adjacent cells. The proposed assumption simplifies the relation among cells in transmission range. Furthermore, it nicely fits the assumption of the local Markov rule [113] required when modelling with Bayesian networks. The Markov rule specifies that variable X_k is independent of its non-descendants given its parents; it is expressed as follows:

$$\left(\mathrm{X_k} \perp \overline{\mathrm{pa}(\mathrm{X_k})}\right)\middle|\mathrm{pa}(\mathrm{X_k}) \qquad (3)$$

With this assumption, the complexity of graph learning algorithm is significantly reduced. Let $\widetilde{X_k}$ $(1 \leq k \leq N)$ denote the set of descendants and ancestors of cell X_k.Using Equation (3), X_k is independent of the remaining nodes in the graph given $\widetilde{X_k}$. The local probability distribution table of X_k $(1 \leq k \leq N)$ can be expressed as follows:

$$\mathrm{p}(\mathrm{X_k}|\mathrm{X_1}, \mathrm{X_2}, \dots, \mathrm{X_{k-1}}, \mathrm{X_{k+1}}, \dots, \mathrm{X_N}) = \mathrm{p}\left(\mathrm{X_k}|\widetilde{\mathrm{X_k}}\right) \qquad (4)$$

Consequently, the joint probability distribution can be recovered using only conditional probability distributions. In the context of vehicular networks, the proposed assumption fits well with the training data. Indeed, vehicles tend to move in small groups of 4-6 adjacent vehicles, especially when density is small [114]. Figure 4.5 shows initial graph structure for three lanes road segment. Edges between non-adjacent cells are omitted. A node in the graph has at most 8 adjacent nodes. To construct an initial graph, coordinator uses a graph indexing method. Nodes in the graph represent cells in transmission range, labeled by cell numbers. Rows represent street lanes. Columns represent the road segment blocks (a block represents a portion of the road segment such that block-length is 6 m) from 1 to $\left\lceil \frac{300}{6} \right\rceil$. A cell, located in the intersection of row y and column x, is assigned cell number *i* computed as follows:

$$i = y \times L - (L - x) \qquad (5)$$

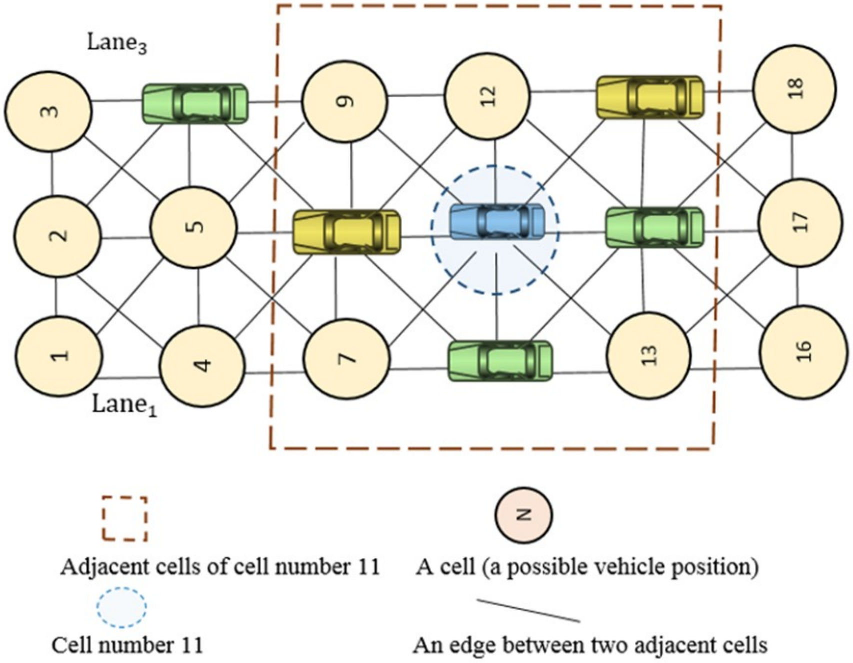


Figure 4.5. Initial graph structure of road segment.

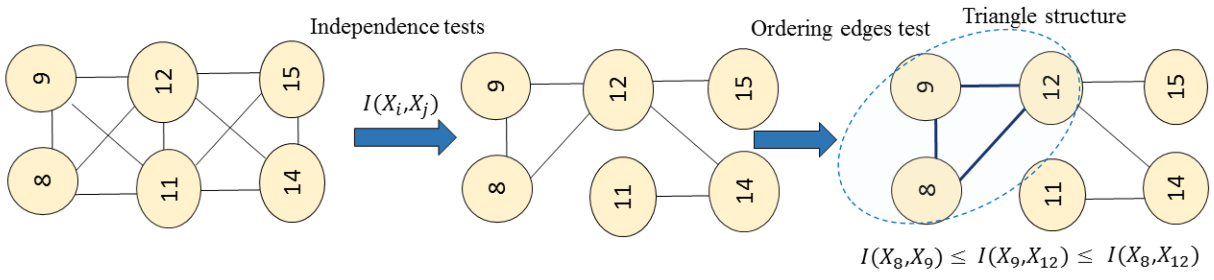
where L in the number of lanes. The graph indexing method enables rapid graph construction; indeed, an edge exists between two adjacent nodes (cells); the indexes of adjacent nodes are simply obtained by increasing/decreasing the row number y and/or the column number x of current cell number i, each time by 1. A node has at most 8 adjacent nodes. Hence, the indexing method enables improvement in the performance of V-PC algorithm (complexity is $\approx O(n)$).

(b) Constructing a non-directed graph

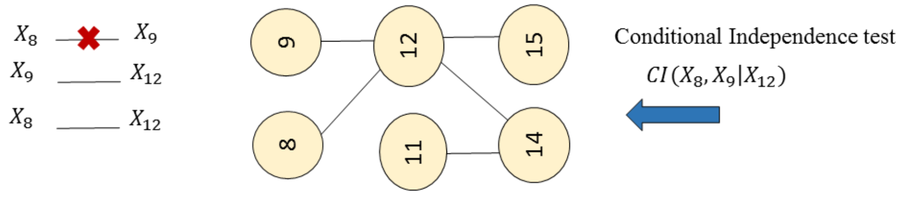
The goal of this step is to construct a non-directed graph using independence and conditional independence tests [111]. First, we execute statistical independence tests to report dependent variables. To determine whether two variables X_i and X_j in $\mathscr{g}$ are dependent, we employ the Chi-square test [115] under the null hypothesis H_0: "X_i, X_j are independent → $p(X_i, X_j) = p(X_i) \times p(X_j)$". The Chi-square test of independence $I(X_i, X_j)$[115] estimates the goodness-of-fit between observed samples of both random variables X_i, X_j and the theoretical probability $p(X_i, X_j)$ of their distribution. It is expressed as follows:

$$I(X_i, X_j) = \sum_{ij} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{6}$$

where E_{ij} is the theoretical probability of $p(X_i, X_j)$ given by the null hypothesis H_0(i.e., $E_{ij} = p(X_i) \times p(X_j)$) . O_{ij} is the probability $p(X_i ,X_j)$ computed by gathering observations of each variable X_i =1 (and $X_j = 1$) from training data. If the pair X_i and X_j has a zero correlation (or smaller than a predefined threshold), then X_i, X_j are independent. In this case, we delete the edge $X_i - X_j$. For example, the edge between X_8 and X_{11} (see Figure 4.6) is deleted because $I(X_8, X_{11})$ is smaller than the threshold. Second, we execute conditional independence tests. For any adjacent cells X_i and X_j, we mark the set of their common adjacent cells.



(1) Initial Graph structure (2) Results of Independence tests (3) Intermediate step



(4) Non-directed acyclic graph

Figure 4.6. V-PC algorithm: Step (b): Construction of undirected acyclic graph: Independence test, Intermediate test (i.e., ordering triangle edges test), Conditional independence test

Let S_{ij} be this set where $|S_{ij}| \leq 4$. For $X_k \in S_{ij}$ $(1 \leq k \leq 4$), we compute the 1st order conditional independence Chi-square test $CI(X_i, X_j|X_k)$ [61] which is expressed as follows:

$$\mathrm{CI}\left(\mathrm{X_i}, \mathrm{X_j} \middle| \mathrm{X_k}\right) = \sum_{ijk} \frac{\left(\mathrm{O}_{ijk} - E_{ijk}\right)^2}{E_{ijk}} \tag{7}$$

where E_{ijk} is the theoretical probability given by the null hypothesis H_0 " X_i and X_j are independent given $X_k \Rightarrow p\left(X_i, X_j \middle| X_k\right) = p(X_i|X_k) \times p\left(X_j \middle| X_k\right)$ ". O_{ijk} represents probability distribution of X_i and X_j conditioned on X_k computed from training data. If the pair (X_i , X_j) conditioned on $X_k$has zero correlation (or smaller than a predefined threshold), the edge $X_i - X_j$ is deleted. This process continues for 2nd and 3rd orders. However, it is important to note that the order in which conditional independence tests are carried out impacts the structure of non-direct graph (e.g., in Figure 4.6, if conditional independence $CI(X_8, X_9|X_{12})$ is carried first, the edge $X_8 - X_9$ may be deleted; if $CI(X_9, X_{12}|X_8)$ is carried first, the edge $X_9 - X_{12}$ may be deleted). In this paper, if one of the edges is going to be removed, we choose the weakest, in terms of dependence, one (i.e., with smallest value).

More specifically, we propose to add an intermediate test between independence tests and conditional independence tests called ordering triangle edges test. For each three variables X_i, X_j and X_k that form a triangle, we measure the strength of dependence between all the three pairs of variables (i.e., $X_i - X_j$, $X_j - X_k$ and $X_k - X_i$) using Equation (4); then, we conduct conditional independence test on the weakest edge. Hence, the weakest edge will be deleted if the conditional independence Chi-square test is smaller than the threshold. Otherwise, we conduct conditional independence test on the next weakest edge, and so on. For each selected node in the graph, conditional dependence test and/or conditional independence test are performed with 8 adjacent nodes. V-PC algorithm locates adjacent cells in the graph using a graph indexing method (see Figure 4.5). In the worst case scenario, the complexity of this step is $\approx O(8 \times n) \approx O(n)$.

(c) Determine V-structures

For each connected triplet (X_i, X_j, X_k), coordinator directs the arcs and adds a V-structure [112] as follows: $X_i \rightarrow X_j \leftarrow X_k$. The complexity of this step is $O(8^3 \times n) \approx O(n)$.

(d) Propagate direction of some arcs

Coordinator directs remaining arcs in a way that avoids the creation of new V-structures and cycles [112]. The complexity of this step is $O(n)$.

Then, coordinator proceeds to compute conditional probability tables in the resulting graph. If random variable X_i has no parent, its conditional probability table is reduced to unconditional. We make use of the iterative algorithm Maximum Likelihood Estimation (EM) [116] to estimate conditional/unconditional probability tables.

4.6. Broadcast Reliability: BR

To achieve high reliability (e.g., 0.99) in its transmission range, a node repeats broadcasting the message a number of times. The timeslots in which a node is allowed to transmit a packet represent its transmission/repetition pattern. Excessive repetitions might cause congestion leading to collisions [117]. Therefore, an optimal number of repetitions must be determined. Link reception quality (obtained from conditional probability tables in the Bayesian graphical model) represents reception probability p_i at a specific receiver/cell i. Let Ng be the number of vehicles in transmission range of the sender, t_k $(1 \leq k \leq L)$ be a random variable that indicates that k repetitions are performed and X_i $(0 \leq i \leq Ng)$ be a random variable taking values 0 and 1. X_i is a Bernoulli random variable $X_i \sim B(p_i(x))$ with reception probability p_i, associated with receiver i. The probability mass function (p.m.f) of X_i can be expressed as follows:

$$\mathrm{p}(\mathrm{X_i} = 1) = \mathrm{p_i} = \mathrm{Q}(\mathrm{x}, \mathrm{t}) = 1 - \mathrm{p}(\mathrm{X_i} = 0) \qquad (8)$$

Let Y_i^k be a geometric random variable $Y_i^k \sim \text{geo}(p_i(x))$associated with receiver i, $(1 \leq i \leq Ng)$. The geometric random variable Y_i^kreturns the first occurrence of successful repetition. Y_i^k is expressed as follows:

$$\mathrm{Y_i^k} = \mathrm{k} \Leftrightarrow \left(\mathrm{X_i^1} = 0, \mathrm{X_i^2} = 0, \mathrm{X_i^{k-1}} = 0, \mathrm{X_i^k} = 1\right) \qquad (9)$$

Probability of first success at the k^{th} repetition, for $k \geq 1$, is defined as follows:

$$\mathrm{P}\left(\mathrm{Y_i^k} = \mathrm{k}\right) = \mathrm{p_i} \times (1 - \mathrm{p_i})^{\mathrm{k}-1} \qquad (10)$$

The integer linear programming (ILP) of the broadcast reliability (BR) problem can be expressed as follows:

$$\mathrm{Max}_{1\le i\le Ng}\left(\mathrm{Min}_{1\le k\le L}\left(Y_i^k * t_k\right)\right) \tag{11}$$

S.c.t

$$\frac{1}{Ng} * \sum_{k=1}^{k=L}\left(\sum_{i=1}^{i=Ng}\left(X_i^k * t_k\right)\right) \ge r_{th} \tag{12}$$

$$t_k, X_i^k \in \{0,1\} \qquad \text{for all } i,k \tag{13}$$

BR is a linear max-min optimization problem [35]. The objective function (11) minimizes the number of repetitions. Constraint (12) guarantees broadcast reliability requirement r_{th}. Constraint (13) is the integrity constraint of the decision variables. Packet reception rate (PRR) is the metric to measure one-hop broadcast reliability [76]. PRR is defined as the ratio of the number of vehicles that successfully received the message in the transmission range, to the total number of vehicles in transmission range. Constraint (12) can be rewritten as follows:

$$\mathrm{PRR} \ge r_{th} \tag{14}$$

To solve BR, we use an iterative procedure. Initially, the number of repetitions n equals one. In each iteration, we increase the number of repetitions n by one and we compute PRR. The procedure returns optimal number of repetitions n_{opt} the first time PRR is greater than r_{th}. It is important to note that PRR is an average metric. Packet delivery ratio (PDP_i) [76] represents the ratio of the number of packets successfully received at a specific receiver i to the total number of packets that are sent. PDP_i is concerned with how an individual vehicle, in cell i, receives the emergency message from the sender. PRR may meet the reliability threshold but PDP_i may not meet the reliability requirement (i.e., receiver i may not receive the emergency message even if PRR meets the requirement). In order to overcome this limitation, the following inequality should be satisfied:

$$PDP_i \ge r_{th} \tag{15}$$

Hence, we derive PRR through averaging PDP as follows:

$$\mathrm{PRR} = \frac{1}{\mathrm{Ng}} \times \sum_{\mathrm{i=1}}^{\mathrm{i=Ng}} \beta_i \qquad (16)$$

where

$$\beta_i = \begin{cases} 1 & if \quad \mathrm{PDP_i} \geq \mathrm{r}_{th} \\ 0 & \quad \mathrm{else} \end{cases} \qquad (17)$$

Each message repetition has reception probability p_i(derived from Bayesian network). The binomial distribution is used to model the number of successes k in n independent repetitions. Let Z_i^n be a Binomial random variable $Z_i^n \sim \mathrm{Bin}(p_i(x), n)$ associated with receiver i, $(1 \leq i \leq N)$. The binomial random variable Z_i^n returns the number k of successful repetitions out of n. Probability of k successful repetitions, for $k \geq 1$, out of n is expressed as follows:

$$\mathrm{P}(\mathrm{Z}^{n}{}_{\mathrm{i}} = \mathrm{k}) = \binom{\mathrm{n}}{\mathrm{k}} \mathrm{p_i}^{\mathrm{k}} * (1 - \mathrm{p_i})^{\mathrm{n-k}} \qquad (18)$$

Hence, the probability of successful packet reception PDP_i associated with receiver i is expressed as follows:

$$\begin{aligned} \mathrm{PDP_i} &= \mathrm{P}(\mathrm{Z}^{n}{}_{\mathrm{i}} \geq 1) = 1 - \mathrm{P}(\mathrm{Z}^{n}{}_{\mathrm{i}} = 0) \\ &= 1 - (1 - p_i)^n \end{aligned} \qquad (19)$$

For n repetitions, we compute new PDP value for each occupied cell using Equation (19). Then, using Equation (16) we compute PRR. If PRR is greater than r_{th} (i.e., If PDP of each cell meets the reliability requirement r_{th}), the iterative procedure will return number of repetitions n_{opt}; here, the number of repetitions n_{opt} is optimal since it corresponds to the first time PRR is greater than reliability requirement r_{th}. Otherwise, we increase number of repetitions n by 1 and we compute new PDP (Equation (19)) values for all cells as well as new PRR (Equation (16)) value.

4.7. Interference Suppression: I-Suppression

In BCRB, repetition patterns are obtained using UPOC [47] with the objective to decrease, ideally avoid, interference caused by hidden terminal problem. Let $\xi = (L, \varpi, \lambda)$ be a set of UPOCs, where L is the code length, ϖ is the code weight and λ is the cross-correlation [47]. Let x= $(x_1, x_2, \dots, x_L)$ and y= $(y_1, y_2, \dots, y_L) \in \xi$ be two codes such that $x \neq y$. Let τ $(1 \le \tau \le L - 1)$ be a circular displacement. The cross-correlation property is defined as follows:

$$\sum_{0}^{L-1} x_i * y_{i\oplus\tau} \le \lambda \tag{20}$$

In order to time-separate interfering nodes, each road segment is assigned a specific code (repetition pattern). A repetition pattern represents a binary sequence of length L in which bit 1 denotes a transmission and bit 0 denotes a non-transmission. In each timeslot, if a node is not transmitting, it is in the idle mode. The code assignment scheme must ensure that cross-correlation property λ $(0 \le \lambda \le \varpi - 1)$ with 2-hop neighboring nodes is zero. In a city streets grid-plan, length of a road segment is in average smaller than 500 meters [118][119]. More specifically, a node along a route can interfere with vehicles located in up to 8 adjacent road segments (4 parallel road segments and 4 perpendicular road segments). In this situation, at least 9 codes (i.e., $|\xi| = 9$) having zero correlation are required. Johnson [87] provides an upper bound for the size of codes $|\xi|$.

$$|\xi| \le \left\lfloor \frac{L}{\varpi} \times \left\lfloor \frac{L-1}{\varpi-1} \times \dots \times \left\lfloor \frac{L-\lambda}{\lambda} \right\rfloor \right\rfloor \right\rfloor \tag{21}$$

where $\lfloor a \rfloor$ is the biggest integer smaller than or equal to a. The zero cross correlation property results in a small number of codes $|\xi|$ [47] (Note that strict orthogonality, i.e., $\lambda = 0$, leads to a very low code cardinality, namely, at most $\frac{L}{\varpi}$). In addition, the cross-correlation constraint for a set of codes is always equal to 1 [47]. Hence, in this paper, cross-correlation property λ is set to $1 (i.e.\ \left\lfloor \frac{L}{\varpi} \times \left\lfloor \frac{L-1}{\varpi-1} \right\rfloor \right\rfloor)$. In a repetition pattern, one collided repetition is allowed without affecting the reliability requirement. Hence, the code weight ϖ is set to the maximum number of repetitions in a frame plus one (because cross-correlation property $\lambda = 1$). To compute ϖ, we determine maximum number of repetitions that achieves reliability requirement r_{th}. If we assume, that for cell i, p_i =0.25 (e.g., very low reception probability) and r_{th}=0.99, then number of repetitions will be 14 (i.e., using Equation (19): $1-(1-0.25)^n = 0.99 \Rightarrow n \approx 14$). In this case, code weight $\varpi \approx 15(=14+1)$. In a frame, a collision can occur only in one time slot without reliability penalty. A vehicle joining a road segment gets the repetition pattern. Once an event occurs, the vehicle computes its optimal number of repetitions n_{opt} (See section 4.6). Then, it maps this number to the repetition pattern of its current road segment. The vehicle uses first $n_{opt}+1$ transmission slots (bit 1) out of ϖ transmission slots. To perform repetitions, we design an overlay, called MAC Repetition Layer (MRL), on the standard MAC Carrier Sensing [38]. MRL is responsible for generating broadcast repetitions. MRL resides between standard MAC layer and Logical Link Control (LLC) layer. The proposed repetition design is compatible with the 802.11 distributed Coordination function (DCF) (no handshake for repetitions, etc.). This makes the proposed repetition scheme compatible with the emerging standards [2] (i.e., IEEE 802.11p amendment for wireless access in vehicular environments (WAVE)) for DSRC [38].

4.8. Forwarders Selection: FS

To relay the message to next hop, BCRB selects multiple next-hop forwarders having best link reception qualities. Multiple forwarders allow avoiding single forwarder limitations; if only one vehicle is chosen as a forwarder and if that vehicle malfunctions or moves away (i.e., leaves the road segment) the message dissemination will be stopped. Let n_F be the number of forwarders. For simplification, we take number of repetitions n_{opt} as a reasonable value for n_F. To ensure successful message reception, forwarders should have high reception probability. Furthermore, it is a known fact that forwarders locations should be close to the border in order to reduce multi-hop latency. First, the sender makes use of link reception quality information to select forwarders. Forwarders having good link reception quality are better choices to successfully receive the message and retransmit it. Consider neighbors' information is available (i.e., using exchanged beacons). Let v^{Ng} denote the set of cells in transmission range having vehicles. For each $x \in v^{Ng}$, the sender extracts the corresponding link reception quality from the most recent CP packet and picks the best n_F elements of v^{Ng} (in terms of link reception quality); then, it creates a set v^q that includes these elements ordered from best to worst (in terms of link reception quality). Second, the sender ensures that the locations of forwarders are close to the border of the transmission range. To achieve this, for each location $x \in v^q$, the sender makes use of a location-shifting technique $\tau(x)$ that moves x to the closest location y to the border while preserving an equivalent (or rather almost equivalent) link reception quality. Let v^F denote the set of resulting forwarders locations. The sender applies a prioritization rule φ_i ($1 \leq i \leq n_F$) to forwarders locations in v^F. φ_i is defined as follows:

$$\varphi_i = \varphi\big(v^F(i)\big) = i \tag{22}$$

The locations of forwarders and their priorities φ_i are included in the emergency message. Such information is useful to coordinate among forwarders in the C-reliability phase.

4.9. Cooperative Reliability: C-Reliability

This phase is executed by forwarders of same hop. The forwarders cooperatively perform optimal broadcast repetitions with the objective to reinforce achieving high broadcast reliability. In addition, the forwarders coordinate to select next-hop forwarders. To achieve this, the forwarders take the role of broadcasting the message iteratively with respect to their priorities φ_i . Each forwarder j $(1 \leq j \leq n_F)$ is assigned a broadcasting timer $\mathrm{T_{ac}(j)}$ and its initial value is indicated in Equation (23). If the broadcasting timer expires, corresponding forwarder j performs $\mathrm{n_{re}}(j)$ repetitions; initial number of repetitions is indicated in Equation (25). Otherwise, the corresponding forwarder is suspended and the value of its broadcasting timer is updated using Equation (24). Similarly, the number of repetitions per forwarder is updated using Equation (26). Initially, highest priority forwarder (with $\max_i \varphi_i$) executes broadcast repetitions (BR) and selects next-hop forwarders while forwarders at lower priorities are suspended. Lower priority forwarders overhear message transmissions and record failed receptions as specified in Equation (26) as long as their broadcasting timer is not expired. Indeed, the repetitions are either successfully transmitted or lost before broadcasting timer of forwarder j expires. If broadcasting timer $T_{ac}(j)$ of forwarder j expires, we distinguish three cases:

(a) Case 1**:**

Current forwarder j failed to receive all repetitions of higher priority forwarder(s) ($\mathrm{n_{re}}(j) = n_{opt}$). This means that higher priority forwarders are malfunctioning or have moved away. Thus, current forwarder j executes forwarders selection (FS) before broadcasting the repetitions.

(b) Case 2:

Current forwarder j successfully received all repetitions of higher priority forwarders ($\mathrm{n_{re}(j) = 0}$). In this case, current forwarder j remains in idle state and suspends its broadcasting timer.

(c) Case 3:

Current forwarder j didn't successfully receive all repetitions of higher-priority forwarders ($n_F > \mathrm{n_{re}(j)} > 0$). This situation usually occurs when higher-priority forwarders leave the transmission range before accomplishing n_{opt} repetitions. Thus, current forwarder j extracts next-hop forwarders list from the already successfully received repetitions and carries out the rest of repetitions as specified in Equation (26).

As long as Equation (28) is not verified, the reliability requirement in current hop is not achieved and the coordination process among forwarders continues.

$$\mathrm{T_{ac}(j) = T_{FS} + n_{opt} * T_{Data}} \tag{23}$$

$$\mathrm{T_{ac}(j) = (j-1) * \Delta s_j} + \mathrm{n}_{re}\mathrm{(j) * T_{Data}} \tag{24}$$

$$\mathrm{n_{re}}(j) = \mathrm{n}_{opt} \tag{25}$$

$$n_{re}(j) = n_{opt} - \left(\sum_{i=3}^{i=j} \left(n_{opt} - \mathrm{n_{re}(i-1)} \right) \right) \tag{26}$$

$$n_{re}(j) = n_{re}(j) + 1 \tag{27}$$

$$n_{opt} = \left(\sum_{i=1}^{i=j} \mathrm{n_{re}(i)} \right) \tag{28}$$

4.10. Simulations

In this section, we evaluate, via simulation, BCRB and three other related schemes, i.e., CPF [49], SAPF [37] and REMD [106] which are closely related to our work (i.e., they propose techniques to improve reliability in multi-hop). We chose also 3P3B [63] as it is a recent emergency message dissemination related work.

A. Experiment Setup

We run simulations using Omnet++ 4.3 [101] as a discrete event simulator and Sumo traffic simulator [100]. Our C++ code uses Veins 2.2.1 [101] for DSRC simulated components [101]. We configured Omnet ++ to model the impact of both distance and obstacles (i.e., buildings and moving vehicles) on the signal propagation. In our work, we choose the Rayleigh propagation model to test BCRB in a more realistic fading environment. Table 4.1 shows the simulation parameters.

Table 4.1. Simulation parameters

Simulation parameter	**Value**
Fading model	Rayleigh [102]
Transmission range (*Tr*)	300 m [120]
WM, Beacon,	100, 72, bytes.
Vehicle density	40-120 cars/km
Reliability requirement r_{th}	0.99
Simulation duration	150 seconds
Coordinator CP rate, Beacon	5, 10 packets/s
Vehicle speed Ve	30-50 km/hour
Message generation rate r	4-5 messages/s

We consider a real city map composed of 3.5 km fragment of a real city street map (www.openstreetmap.org/). Each road segment contains two lanes. We consider the following simulation scenario: a set of vehicles with a predefined penetration rate (i.e., the percentage of vehicles that originally disseminate emergency messages compared to vehicle density) of 5% act as message sources (A source is the car trying to broadcast an emergency event). During simulation, the source vehicles broadcast generic emergency messages at a rate of r messages/s. Simulation results are averaged over 10 runs and characterized by a 95% confidence interval.

The performance parameters, we consider in the evaluation of BCRB, are: (a) packet reception ratio (PRR) *(%)*: The percentage of vehicles that receive the disseminated message; (b) Average propagation delay *(msec)*:The average length of time between the time a message is transmitted by the source and the time it is received by the vehicles in the target area; and (c) Network overhead *(bytes/road segment)*: The average total number of bytes of all packets used in the message dissemination process except beacon messages since they come with vehicular networks.

B. *Validation*

The objective of this section is to validate the analytical findings of BCRB using Omnet++ simulations. More specifically, we show the estimation of link reception quality as a function of training data size. We also validate the followings: (a) link reception quality $p(X)$ (Equation (4)); (b) packet reception rate PRR (Equation (16)); and (c) optimal number of repetitions n_{opt} (Equation (11)).

Figure 4.7 shows the variation of the average accuracy of link reception quality estimation plotted with the length of the training data collection duration. We observe that the average accuracy increases with the length of the learning phase for all vehicle densities.

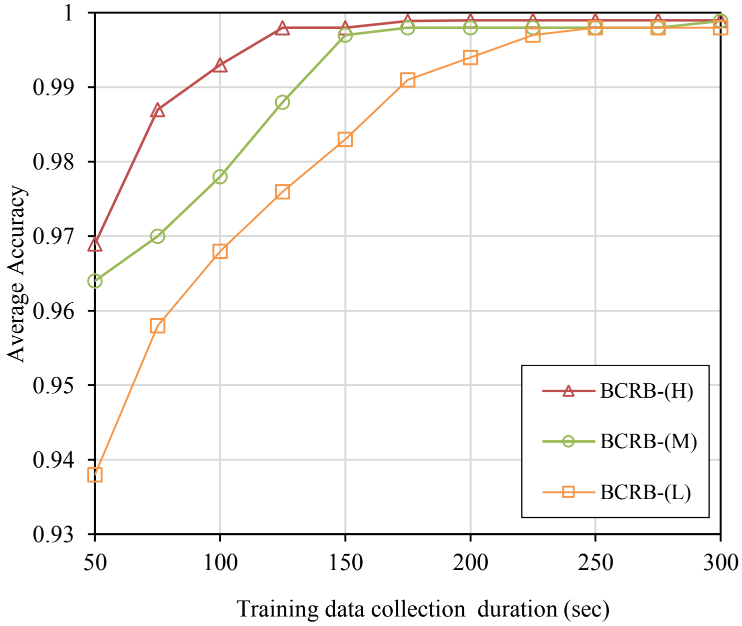


Figure 4.7. Link reception quality estimation accuracy vs. training data collection duration

This can be explained by the fact that the size of training data is proportional to the length of the training data collection duration; indeed, the number of samples in the training data equals to the training phase duration, multiplied by both beacons rate and the number of vehicle per road segment. This is expected since the larger the training data set is, the more accurate the estimated joint probability distribution will be and the more accurate the conditional probability table estimation result (link reception quality estimation). Note that, theoretically, there is no relationship between size of training data and the estimation accuracy. At 175 seconds, the average estimation accuracy is higher than 99%, for all densities. We refer to such a value as an optimal learning delay.

Figure 4.8 shows link reception quality $p(X)$ (taken for optimal training data collection duration) plotted against vehicle density. As expected, $p(X)$ decreases when vehicle density increases. This is expected since traffic of periodic beacons increases with density resulting in unreliable wireless links. This observation validates the use of $p(X)$ to assess 802.11p link reception quality in cells. The analytical results closely follow simulation results for all densities. In average, the difference between the analytical and the simulation results falls below 2%.

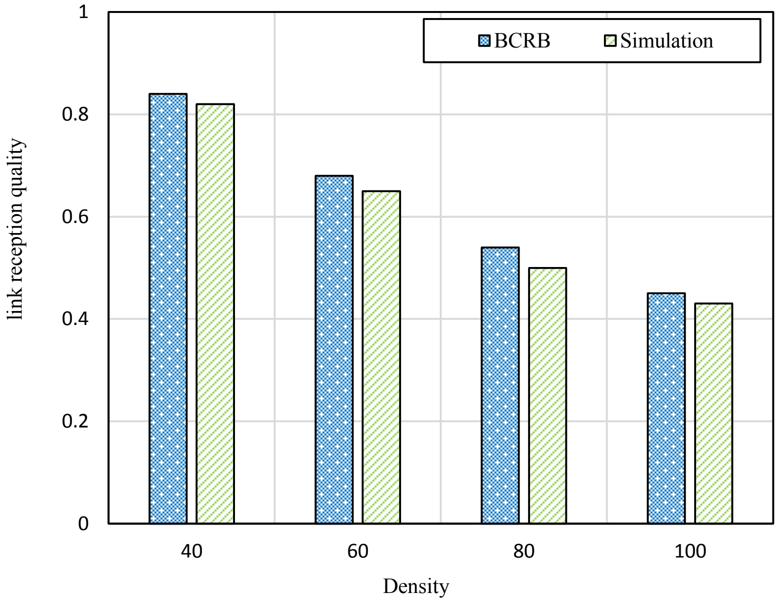


Figure 4.8. Link reception quality vs. density

Figure 4.9 shows PRR plotted against the number of repetitions n for three density levels. As expected, we observe that PRR increases with the number of repetitions. This observation validates the basic idea of broadcast repetitions. Again, the analytical results closely follow simulation results. The analytical approach performs well in all densities of vehicles. The difference between the analytical and the simulation results is about 1.75%.

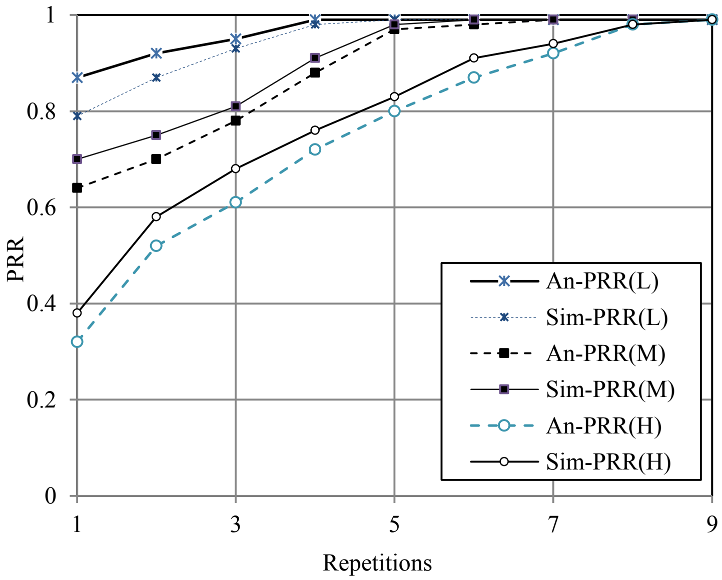


Figure 4.9. PRR vs. repetitions

Figure 4.10 shows repetitions n_{opt} plotted against density. We observe that the analytical model is very accurate: analytical results practically coincide with the simulation results, in both medium and high density cases.

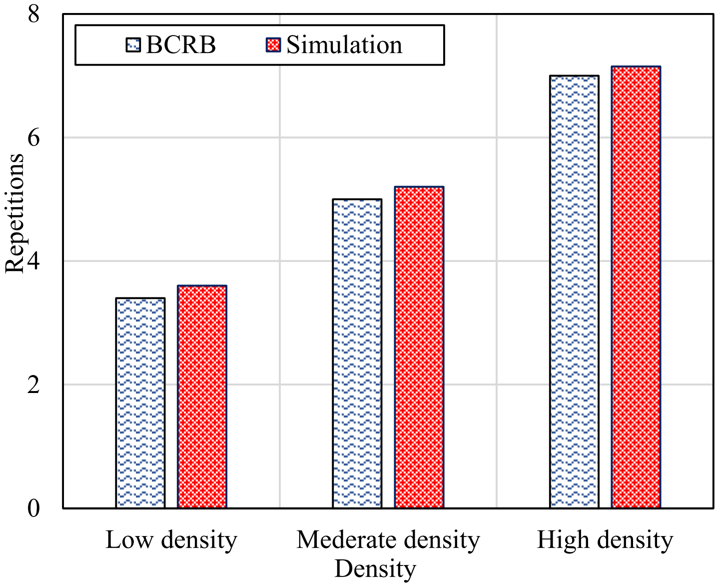


Figure 4.10. Repetitions vs. Density

C. Comparison

In this section, we evaluate the performance of BCRB for city scenarios in terms of PRR, average delay, and network overhead. The performance results are shown in Figures (4.12)-(4.14). All simulation results are obtained with 95% confidence interval.

Before presenting the details of this evaluation, we first compare link reception quality estimation accuracy of BCRB and REMD [106]. Figure 4.11 shows the variation of the average accuracy of link reception quality estimation with vehicle density; here, the training data collection duration assumes 150 seconds. We observe that BCRB is more accurate than REMD for all densities. The low performance of REMD is related to its non-realistic analytical model of link reception quality. Indeed, REMD uses curve fitting and polynomial modeling to estimate link reception quality in each cell, independently of adjacent cells. For each cell, the amount of collected data (collision rate and signal power attenuation rate) increases with vehicle density. In low density scenarios, random errors in data points can cause problems with curve fitting since the number of data points is too small. In high density scenarios, the series of data points used to find the "best fit" curve increases resulting in good accuracy (more than 97%).

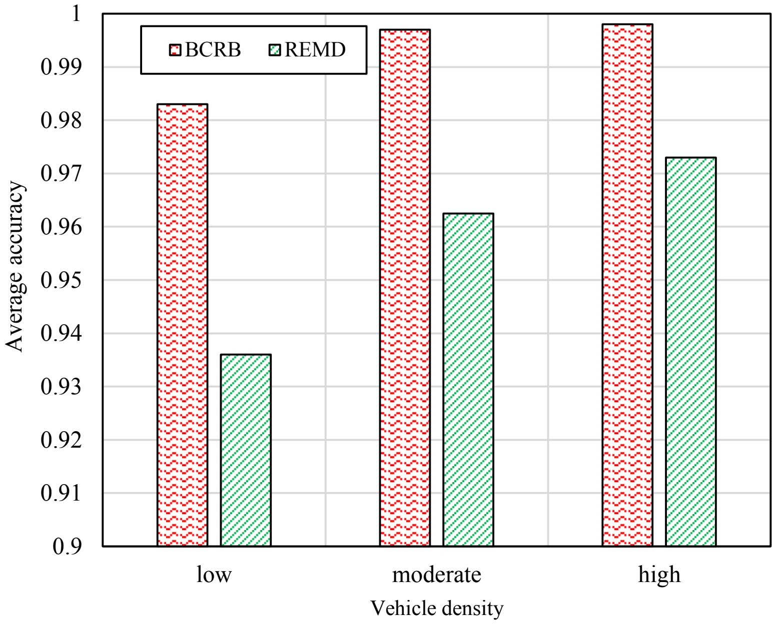


Figure 4.11. A comparison of Link reception quality estimation for BCRB and REMD vs. vehicle density

This is because more data allow for the averaging out of random error. In contrast, BCRB takes into account the causal relationship between adjacent cells to infer link reception quality. In low density scenarios, even if some cells are vacant, occupied cells (i.e., cells with vehicles) allow for joint probability estimation and thus for inferring link reception quality in vacant cells.

Figure 4.12 shows the variation of PRR with the vehicle density. Initially, when the density is low, we observe that PRR ranges between 95% and 99% for all schemes. Then, as the density goes up, this rate gradually goes down to about 45% for 3P3B, 70% for CFP and 64% for SAPF. In contrast, we observe that BCRB and REMD successfully have a PRR of 99% for all densities. The main reason for PRR degradation when using CFP , SAPF and 3P3B is that when vehicle density increases, channel conditions vary (as emulated by the Rayleigh model) resulting in bad link reception quality in transmission range. In addition, in city environment, buildings and moving vehicles impact negatively the link reception quality; when coupled with high vehicle density. The worst performance of 3P3B is caused by its forwarder selection mode. 3P3B selects farthest forwarder; in high densities, the forwarder may have low link reception quality resulting in packet loss.

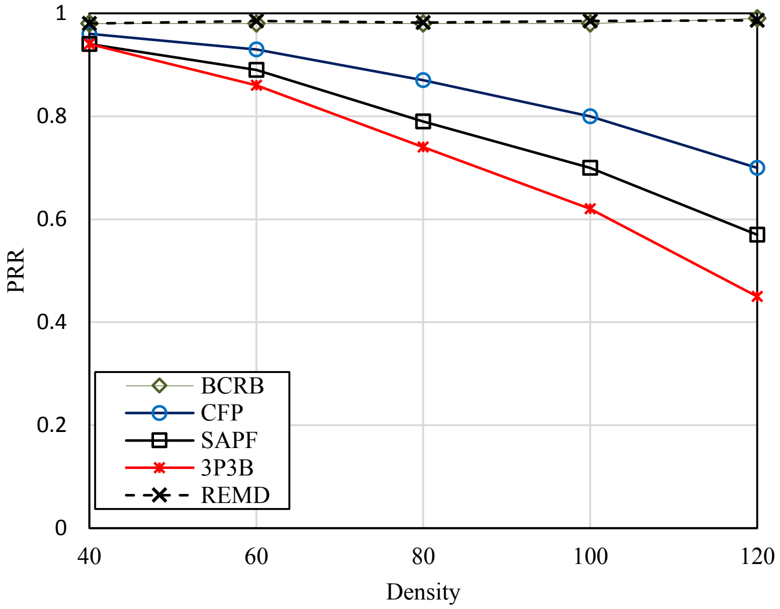


Figure 4.12. PRR vs. Density

The key component (RTB/CTB handshake) in 3P3B is vulnerable to collisions and interference in adverse vehicular environment. In addition, overhearing messages doesn't guarantee high PRR for intermediate nodes. PRR provided by CPF drops when vehicle density goes up. This is because the locations of selected forwarders suffer from shadowing and multipath fading. This situation becomes serious when vehicle density (moving obstacles) increases. In such a situation, whatever the number of repetitions within a time frame, CPF cannot account for variable channel conditions. In SAPF, a node decides to broadcast based on vehicles speed. This decision doesn't account for signal propagation issues resulting in high packet loss. However, BCRB (resp. REMD [106]) dynamically estimates link reception quality; then, it selects best forwarders having good link reception quality. Then, BCRB (resp. REMD) carefully determines optimal number of broadcast repetitions according to network conditions in order to satisfy reliability requirement.

Figure 4.13 shows average delay plotted against vehicle density. We observe that initially all schemes achieve a very reasonable delay for 40-60 vehicles/km. When vehicle density goes up, we observe that delay provided by CFP, 3P3B and SAPF increases. The worse performance of 3P3B is related to the fact that, in dense urban scenarios, control packets are vulnerable to packet loss.

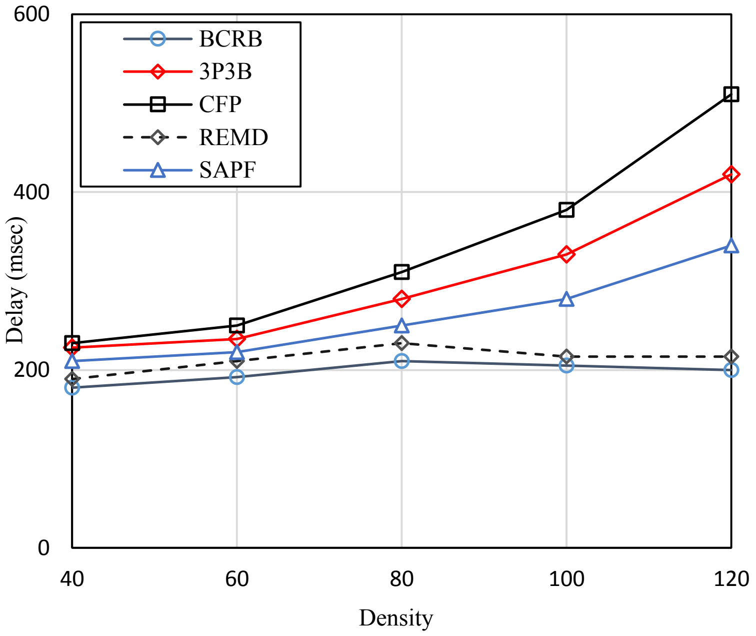


Figure 4.13. Delay vs. density

In such situations, 3P3B performs more retransmissions in order to recover failed receptions; exchanged packets (i.e., RTB/CTB packets) are vulnerable to packet loss resulting in higher delays. However, for all densities, both BCRB and REMD successfully achieve a delay smaller than the recommended delay threshold for safety applications [27][121]. This is due to the fact that (a) forwarders selection considers distance to sender in addition to link reception quality; and (b) fast repetitions is used to meet requirements in terms of delay. It is important to note that BCRB achieves a slightly lower delay (e.g., 9% for 40-60 vehicles/km) compared to REMD for all nodes densities. This is because, in low density scenarios, BCRB is more accurate than REMD in estimating link reception quality. Thus, BCRB carefully selects forwarders to be closer to the border. We also observe that the gap between delays recorded by CFP and BCRB/REMD gradually increases with vehicle density; this demonstrates that packet loss due to signal propagation issues critically impacts the delay performance of CFP.

Figure 4.14 shows that BCRB generates relatively low network overhead when compared to REMD (e.g., REMD generates 17% more network overhead than BCRB, for 100 vehicles/km). This can be explained by the fact that REMD is less accurate than BCRB in estimating link reception quality and thus it may perform more repetitions than BCRB.

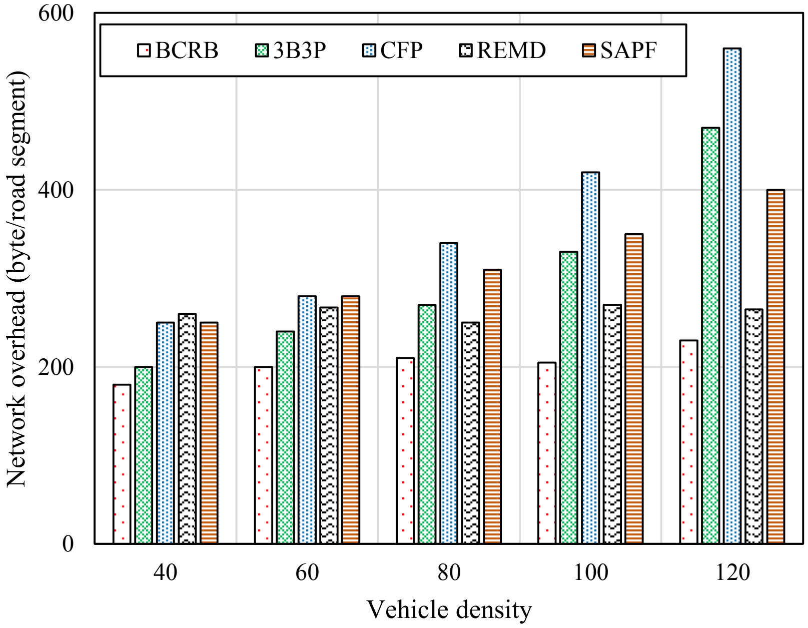


Figure 4.14. Network overhead vs. Density

Note that generated CP packets overhead in BCRB is smaller than generated message repetitions overhead in REMD. More importantly, the total network overhead of both BCRB and REMD increases slowly with density. A possible explanation of this slow increase is related to the optimized broadcast repetitions mechanism in BCRB and REMD which avoids redundant rebroadcasting. In opposition, 3P3B and SAPF continue retransmitting in order to recover failed receptions. We conclude that BCRB provides the best reliability compared to existing related schemes while, at the same time, provides a best delay that satisfies the requirements of safety applications.

4.11. Conclusion

In this paper, we presented a novel reliable emergency message dissemination scheme for urban networks. BCRB aims at guaranteeing high reliability at each hop while preserving low end-to-end delay. BCRB, based on Bayesian networks, accurately infers 802.11p link reception quality in cells. Using this information, BCRB determines optimal number of broadcast repetitions in order to guarantee reliable broadcast in vehicular networks. Furthermore, BCRB assigns zero-correlated Uni-Polar Orthogonal Codes to adjacent road segments in order to cancel interference caused by hidden terminal problem. In multi-hop, BCRB carefully selects multiple forwarders and their locations. Forwarders of same hop cooperate with the objective to achieve high reliability in intermediate hops. We validated, via simulation, the proposed graphical model of 802.11p wireless link reception quality in transmission range. Furthermore, simulation results show that BCRB achieves better performance compared to existing related schemes. This result makes it a good emergency message dissemination scheme in urban environments. Future work will mainly cover the development of new methods for rapid learning algorithms in vehicular networks.

Chapter 5

Optimal Gateway Placement and Reliable Internet Access in Urban Vehicular Environments

Wiem Benrhaiem, Abdelhakim Hafid, and Pratap Kumar Sahu

Abstract

Internet of Vehicles requires reliable Inter-Vehicular communications. Such a requirement is challenging since the wireless communication channel is very erroneous and lossy in city environments. A lot of solutions for connecting vehicles to the internet have been proposed. However, existing multi-hop gateway discovery solutions do not consider, a key issue, the unreliability of broadcast in city environments. In this paper, our objective is to find out the minimum communication hops, with very high reliability (e.g., 97%), to gateways. To accomplish this, we model the gateway placement problem (called GP) as a k-center optimization problem. We solve it in $O(n^2 * log(n))$ time using a (2-1) dimension reduction technique. We make use of M-HRB [31] to discover reliable multi-hop paths to gateways. Simulation results demonstrate that applying M-HRB with GP provides high packet reception rate and generates smaller end-to-end delay compared to existing solutions. Furthermore, our proposal makes efficient use of wireless channel bandwidth.

Key words: Gateway placement, reliability, internet of vehicles, vehicular networks, k-center optimization problem.

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5.1. Introduction

The main contribution of Intelligent Transportation Systems (ITS) is to significantly increase road safety. However, ITS is attracting the interest of network operators and service providers for the provision of infotainment services [6]. In modern cities, people spend a considerable amount of their time commuting by car from one place to another. To improve the driving experience and making trips more productive, a plethora of infotainment applications including content download, media streaming, VoIP, social networking, gaming, cloud access, etc., have been made available to vehicular users anytime and anywhere. This calls for vehicular communication networks to support Internet services in vehicles [10]. Indeed, In-vehicle Internet access [10] allows a vehicle to connect to the Internet through an Internet gateway. Traditionally, an internet gateway is an RSU, installed in fixed position along a roadside. A main benefit of such an infrastructure is to relieve poor network connectivity (e.g., RSUs can increase the overall coverage of a vehicular network and enhance network performance (i.e., delay) between disconnected vehicles) [11]. Unfortunately, Internet access through RSUs requires pervasive RSUs to ensure each vehicle is in RSU's transmission range [11] (i.e., the typical range of an RSU is 250m). Such a requirement incurs high infrastructure deployment cost. Several contributions [12][13][14][15][16] are proposed to optimally place RSUs. Indeed, deploying a new RSU needs intensive investigation [11]; for instance, the land where to place a new RSU may be private requiring owner permission. It may be difficult, if not impossible, to get such a permission. Therefore, deploying new RSUs often requires a large amount of investment and elaborate design, especially at the city scale. Consequently, internet access systems that rely only on roadside infrastructure are impracticable to be implemented. Recently, the concept of LTE-connected vehicles [17] (i.e., a vehicle equipped with 802.11p and UTRAN interfaces) has received a lot of attention. Once in the range of a LTE base station, the vehicle gets internet access. Actually, LTE provides a robust mechanism for mobility management of vehicles [18] (i.e., supports a data rate of 10 Mbps with a speed up to 140 km per hour). LTE also fits the bandwidth demands and the quality of service requirements of infotainment applications [18]. However, mobile data is experiencing explosive growth [19]; this makes LTE cellular infrastructure bandwidth not able to keep up with connecting high number of connected vehicles [20]. Also, it has been reported that cellular infrastructure connectivity cannot evolve once it is installed [17]. Furthermore, many vehicles incur frequent handoffs, because of high mobility, requiring higher bandwidth [21]. Hence, allowing only some connected vehicles to operate as gateways (mobile gateways) to other vehicles may be effective [22]. Several contributions [23] [24] [25] [26] have focused on proposing various Internet access systems using connected vehicles as gateways. Getting internet access through either RSUs ([12] [13] [14]) or connected vehicles ([23] [24] [25] [26]) relies on multi-hop communication links. Typically, a vehicle connects to a gateway in its vicinity. In case no internet gateway in the range, a vehicle relies on multi-hop communications to connect to a gateway beyond its transmission range. A gateway discovery protocol is required to discover routes (i.e., an established route is a fixed succession of nodes between the source and the destination) to gateways not in the range. Random loss in wireless ad hoc networks is caused by lossy wireless communication channels and node mobility. Typically, transmission in wireless medium is always vulnerable to packet collisions and interferences due to various wave propagation issues such as signal attenuation, noise and jitter. These effects are quite predominant in vehicular networks in the presence of high rise buildings making vehicular networks quite unreliable. Achieving very high reliability in the presence of all kinds of wireless network vulnerabilities is a major challenge in vehicular networks. Gateway discovery protocols use IEEE 802.11p broadcast communication mode. However, IEEE 802.11p broadcast does not support acknowledgement. Therefore, losses of messages due to packet collisions, poor channel conditions, etc., cannot be easily detected. Gateway discovery protocols should be able to establish reliable paths in the presence of all such conditions. In this paper, we introduce a reliable multi-hop internet access system (called RICS) for urban vehicular environments. Basically, we make use of both LTE-connected vehicles and the already deployed RSUs infrastructure as gateways. RSUs have a considerable impact on network reliability, as they are fixed reliable nodes [55]. Because of random mobility of vehicles, there is the possibility of network fragmentation. Static RSUs may act as bridges between fragmented groups of vehicles [11]. LTE-connected vehicles enhance gateways availability because adding such vehicles (e.g., buses and taxis) doesn't require additional infrastructure (e.g., land). In [22], it has been reported that using connected vehicles as gateways increases the probability, for moving vehicles, to set up paths with fewer hops. To ensure reliable multi-hop In-vehicle Internet access, our objective is to find out the minimum possible communication hops, from a requesting vehicle to a fixed/mobile gateway, with high reliable message dissemination (e.g., 97%). To accomplish this, we model the gateways placement problem (called GP) as a 2-dimentional k-center [56] optimization problem. This problem is known to be NP-hard. We make a dimension reduction of the optimization problem and propose an exact time resolution algorithm to solve it. On top of the minimum communication hops, we implement a gateway discovery protocol M-HRB [31] which exploits the reception quality of 802.11p wireless links to establish high reliable communication paths. The remainder of this paper is organized as follows. Section 5.2 presents related work. Section 5.3 presents our assumptions and the basic idea of the proposed scheme. Section 5.4 presents the gateway placement optimization problem. Section 5.5 presents the gateway discovery protocol. Section 5.6 described the proposed solution. Finally, Section 5.7 concludes the paper.

5.2. Related Work

Several gateway discovery schemes (i.e., [50][26][51][52]) have been proposed in the literature. These schemes can be classified into three categories: (1) Proactive approaches [50][52], where gateways advertise themselves in the whole network. In [50], the gateway with the maximum route connection's duration is selected (The route connection's duration represents the time elapsed before a connection breaks along the route, which is estimated using traffic density and distance to gateway). In [52], gateways employ the concept of connected dominating set (CDS) to retransmit the advertisement message. Every vehicle is either in CDS or adjacent to at least one node in CDS. The CDS nodes are selected using route lifetime parameter. The route lifetime is the minimum of the lifetimes of its constituent links; link lifetime is the time difference between link initiation and link breakage/termination; (2) Reactive approaches [26][51][53], where vehicles (called requesters), that want internet access, need to flood the network for gateway discovery. In [26], the discovery protocol uses location and speed of vehicles to predict when the route to the gateway will break and preemptively creates new routes to replace old ones before they break. In [51], the discovery protocol selects few forwarding nodes to reduce overhead of the protocol in [26]. Speed of neighboring vehicles is a main parameter to predict lifetime of links between two vehicles. The gateway with the maximum predicted route lifetime to the source is selected. In [53], the route that can stay longer (i.e., has biggest lifetime), between the vehicle and the gateway, is selected. The discovery process makes use of predictable vehicle mobility, which is limited by traffic pattern and road layout. We conclude that reactive schemes suffer from poor scalability in discovering gateways as all vehicles send requests; and (3) Hybrid approaches [75][54], where gateways advertise themselves to their neighbors (1 or n hops away); then, requesters send packets to find a gateway in these advertisement areas. The selection of advertisement zones depends on the dimension of the network. A small advertisement zone could result in high reactive overhead, and a large advertisement zone could result in high proactive overhead. In [54], the authors use the characteristics of vehicle movements (e.g., speed and direction of movement) to predict the future behavior of vehicles, and to select a route with the longest lifetime to connect to the wired network. In [75], the position of the destination and the position of neighboring nodes are used to forward data without establishing routes in the advertisement area. Any node that ensures progress toward the destination can be used for forwarding. The forwarding decision is based on the position of destination vehicle and position of one hop neighbors. However, the link to the selected node may be unreliable in harsh network conditions leading to packet loss. From above discussions, we can conclude that the route discovery schemes do not guarantee reliable communication, in city settings. Existing schemes (e.g., [26][51][53][54]) make use of link stability metric, which is based only on mobility metrics (e.g., relative motion between neighboring vehicles, speed, etc.), to determine paths to gateways. In city settings, such a selected route can be broken frequently owing to the high mobility of vehicles. In [22], it has been proved that the number of breakages of a path increases with the number of hops in the path. Thus, the node centric view of the routes in [26][51][52][54][53] leads to frequent broken routes in the presence of VANETs’ random loss (high mobility and lossy wireless communication channel). Consequently, many packets can be dropped, and the overhead due to route repairs or failure notifications significantly increases, leading to low delivery ratios and high transmission delays of advertisement messages. Thus, vehicles that are far away from the mobile gateway transmission range will have limited or very poor internet connectivity.

5.3. Proposed Scheme

5.3.1. Assumptions

In this chapter, we consider a scenario where vehicles are moving on urban streets. We choose a city map where the length of a road segment is random. We assume that (1) vehicles are equipped with a Global Positioning System (GPS) and digital road maps; (2) RSUs (equipped with 802.11p interface and wired access to the backbone internet) are distributed randomly with a predefined density; (3) all vehicles are equipped with IEEE 802.11p [18] wireless technology and computation capabilities; (4) LTE-connected vehicles (equipped with both IEEE 802.11p and LTE interfaces) are distributed randomly with a predefined density; (5) connected vehicles are in the range of an LTE base station; (6) obstacles (e.g., buildings) exist; thus, this may impact communication among vehicles; and (7) vehicles density information is transmitted according to the scheme in [122] to a central server, for each time period T_g (e.g., T_g =1 minute).

5.3.2. Basic Internet Access Strategy

Figure 5.1 shows the gateways architecture providing vehicle-to-Internet communication. A set of static gateways (RSUs) and mobile gateways (Connected vehicles) are distributed randomly. Vehicles intend to get internet connectivity.

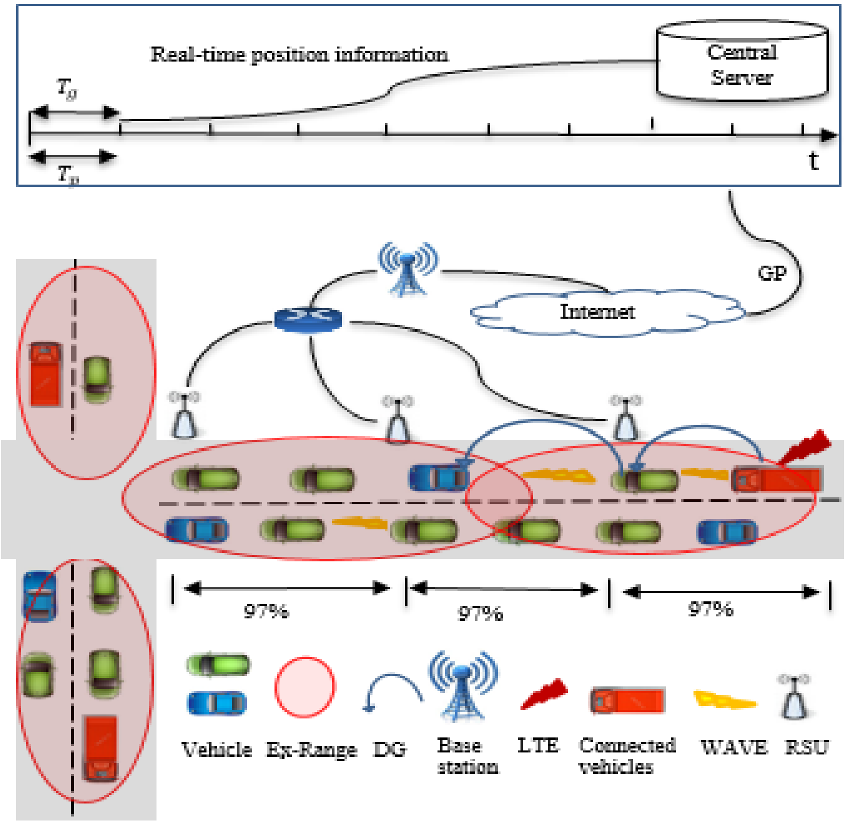


Figure 5.1. Internet access architecture

A vehicle *v* connects to a gateway, if it exists, in its direct vicinity. Alternatively, *v* uses multi-hop communication to access a gateway beyond its transmission range. Given the density information, the basic idea of the proposed scheme is to select a predefined number of gateways *k* and their locations to cover all vehicles. Each gateway sets the minimum radius, in terms of communication hops, of its advertisement area forming an Extended Range (Ex-Range). The gateway provides reliable internet access to all vehicles in its Ex-Range using multi-hop communication. The proposed scheme consists of two main phases: (1) Gateway Placement Phase (GP), where the gateways define their minimum communication hops with the objective to cover all vehicles (See Section 5.4); and (2) Gateway Discovery Phase (GD), where each selected gateway applies a gateway discovery protocol in the network region defined by the number of hops determined in the first phase. The gateway discovery protocol exploits the quality of 802.11p wireless link of neighbors to ensure a very high reliability requirement of internet connectivity (e.g., r_{th}=97%) in urban settings (Section 5.5).

5.4. Gateway Placement

5.4.1. Network Model

Basically, as defined in [31], each street is divided into a number of zones. The length of each zone is same as the transmission range of a vehicle (i.e., $Tr = 250$ meters). Each zone is divided into partitions with predefined length (e.g., length of a Car = ~ 6 meters) to have either 1 vehicle or no vehicle in each cell. Thus, a cell represents a possible vehicle location. We define transit-time T_s (e.g., $T_s = 0.2$ seconds) as the cell transit time. In a cell, during T_s, moving vehicles are assumed to be stationary. We assume no fragmentation in the network. For each T_s, we model the network connectivity graph as an undirected weighted connected graph G = (V, E), where V denotes the set of nodes (vehicles and RSUs) and E ⊆ V × V the 802.11p communication links between neighboring nodes. The number of nodes is $|V| = Ng + Nv$, where Ng is the number of gateways and Nv is the number of vehicles. We consider a 2-dimensional metric space $(V \times V, Hop)$ to model the distance (i.e., number of hops) between two vertices in G; the weight of an edge $e \in E$ is equal to 1. Let $(u, v) \in V$ denote two nodes in G and $\mathrm{Hop(u,v)}$ the minimum number of hops between u and v.

$$\mathrm{Hop(u,v)} = \mathrm{Hop(u,y)} + \mathrm{Hop(y,v)} \tag{1}$$

where y is a vertex in G. $\mathrm{Hop(u,y)}$ is the shortest path between u and y. $\mathrm{Hop(y,v)}$ is the shortest path between y and v. $\mathrm{Hop(u,v)}$ is the shortest path between u and v.

5.4.2. Problem formulation

The gateway placement problem (GP) consists of selecting a predefined number of gateways k with the lowest number of communication hops to cover all vehicles. Thus, the maximum distance (in terms of hops) of any vehicle to its gateway is minimized. Let g_i, $1 \leq i \leq Ng$, denote a binary variable that indicates whether gateway i is selected and v_j ,$1 \leq j \leq Nv$, denote a binary variable that indicates whether vehicle j is covered (by a selected gateway) and t_{ij} denote a binary variable that indicates whether vehicle v_j is covered by gateway g_i. The integer linear programming (ILP) [123] of the GP problem can be expressed as follows:

$$\mathrm{Min}_{1\le i\le Ng}\left(\mathrm{Max}_{1\le j\le Nv}\left(\mathrm{Hop}(g_i, v_j) * t_{ij}\right)\right) \quad (2)$$

S.c.t

$$\sum_{i=1}^{i=Ng} g_i \le k \quad (3)$$

$$g_i \ge t_{ij} \quad \forall i, \forall j \quad (4)$$

$$\sum_i t_{ij} \ge 1 \quad \forall j \quad (5)$$

$$g_i, v_j, t_{ij} \in \{0,1\} \quad \forall i, \forall j \quad (6)$$

The objective function (2) determines the minimum number of hops that enables every vertex (vehicle) to be connected to one of the *k* Internet gateways. Constraint (3) ensures that the number of gateways is not greater than k. Constraint (4) guarantees that a gateway is placed before being used. Constraint (5) guarantees that each non-gateway vehicle can reach at least one of the gateways. Constraint (6) is the integrity constraint of the decision variables. In contrast to cellular networks, in vehicular networks, the availability of a gateway changes frequently due to high mobility. Hence, a vehicular gateway enables short connection duration when compared to the connection duration to a cellular base station [50][124][125]. In our model, the GP problem is resolved each update time T_p. The update time T_p represents the average road segment transit time (e.g., $T_p = 62s \approx 1$ minute, average length of road segment is 500 m and average vehicles speed is 30 kilometer/hour). The central server (Figure 5.1) provides real-time density information each 1 minute [126]. Therefore, $T_p \approx T_g$.

- *Proposition*: GP is NP-hard.
- *Proof*: To prove this, we use a reduction from the Euclidian k-center [127] problem (a variant of the Facility Location Problem (FLP) [127]). Given a two dimensional metric space with a set *S* of *n* points in the plan and a positive integer *k*, the k-center problem is to find *k* congruent disks of minimum radius *r* that cover S. The Euclidian distance between two points in *S* is denoted by *d*. In the k-center problem, the radius *r* of a disk represents the maximum distance *d* from a point, in S, to its closest disk center. The Euclidian distance *d* between any two points in S satisfies the triangle inequality [18]. The k-center aims to minimize r. In the GP problem, the *k* Internet gateways are referred to as the centers of the network connectivity graph G. As for

the distance *d*, the linear equality (in terms of hops) property defined in Equation (1) refers to the triangle inequality property. The length of the path which is longest among all shortest paths represents the radius r of a disk. Note that, in GP, a path is a route from a vehicle to its closest gateway. Thus, the GP problem is an example of the 2-dimentional k-center problem which is known to be NP-hard [56]. Consequently, GP is NP-hard. Despite its NP-hardness, the GP problem could be solved using a simplified model [128]. In fact, it is quite natural to assume that Internet gateways moving one beside the other on parallel street lanes cover the same set of vehicles. Similarly, vehicles moving one beside the other on parallel street lanes are in the range of the same Internet gateway. We call this assumption a 2-1 space dimension reduction of a city street. This assumption can be geometrically proved.

- *Proposition:* The city street is 2-1 dimension reducible.
- *Proof:* Let us consider a 2-dimensional representation of a city street (see Figure 5.2), independently from the road structure (*i.e.*, straight or curved), the number of intersections, the number of lanes and the length of the street.

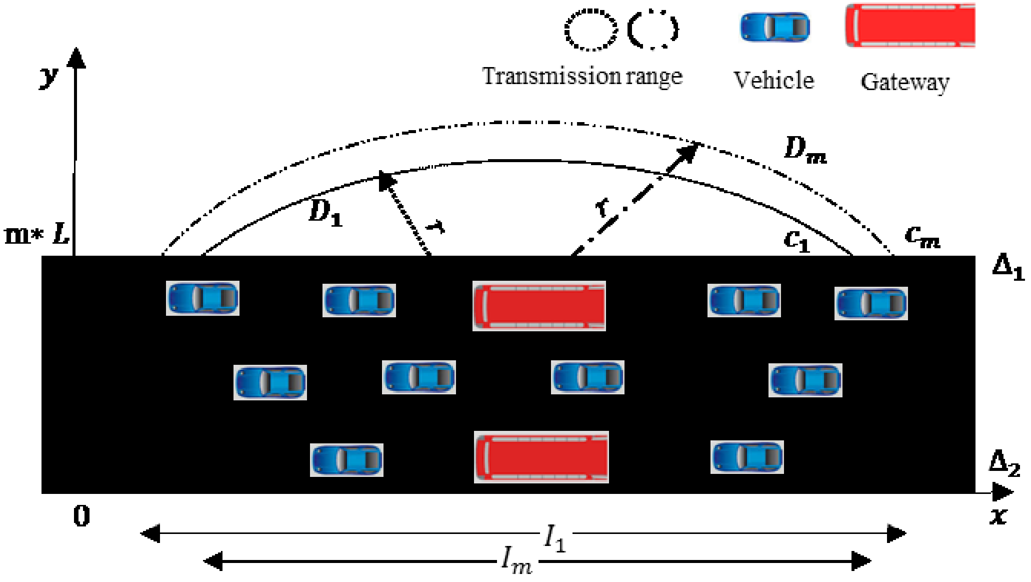


Figure 5.2. Candidate gateways locations

The horizontal direction from left to right is X-axis (X-axis represents a possible street lane); the vertical direction from down to top is Y-axis. The Y-axis values correspond to street lanes (ranging from 1 to m+1, where m is the number of street lanes, the street side where RSUs are placed is considered as a virtual street lane with no vehicles. Thus, the maximum value in Y-axis is m+1). An X-axis value is proportional to the cell length [31]. X-axis values are proportional to cell length (6 meters). Given two gateways locations o_1 and o_2 at the same X-axis value, let disk $D_1(o_1, r)$ and disk $D_2(o_2, r)$ represent the wireless coverage of gateways o_1 and o_2 respectively. r is the disk radius. In figure 2, we suppose r=1. Let Δ_1 and Δ_2 represent the street border lanes. The equation of any straight line, called a linear equation, can be written as: "y = ax + b", where a is the slope of the line and b is the y-intercept. Thus, Δ_1 corresponds to y=m , where m is the number of street lanes, and Δ_2 corresponds to y=0. Let c_1 and c_m be the X-axis coordinates of the rightmost intersection points of the street border lane Δ_1 , with D_1 and D_2, respectively. The value of $|c_1 - c_m|$ is negligible when compared to a vehicle location (6 meters [31]).

$$|c_m - c_1| \ll 6 \tag{7}$$

Therefore, gateways that have the same X-axis values cover the same set of vehicles. Similarly, vehicles that have the same X-axis value are covered by the same gateway. We denote by p_i , $(1 \le i \le \left\lceil \frac{n}{m+1} \right\rceil)$, n is the total number of nodes on the street and m is the number of street lanes, the orthogonal projection of the nodes (vehicles and RSUs) onto the X-axis. Thus, p_i represents a virtual representation of all street nodes on the same straight line; this line models the street.

5.4.3. One-dimensional GP

In this section, we make use of a 2-1 dimension reduction [130] of GP. We convert the GP problem from a $(V \times V, \mathrm{Hop})$ dimensional space to a (V, Hop) dimensional space. Given the one-dimensional representation of the city street, we define the one-dimensional GP problem on a line as follows: Given a set S of n points (i.e., vehicles) lying on a line and an integer k ≥ 1, find k intervals with centers (i.e., gateways) on that line such that the union of the intervals covers S and the maximum radius of the interval (half of its length) is minimized. The basic idea of the 2-1 dimensional reduction algorithm is to represent the nodes (i.e., vehicles and RSUs) along the street by points p_i obtained by orthogonal projection of the street nodes onto the X-axis. The orthogonal projection of the nodes (vehicles and RSUs) on the X-axis results in three categories of points: (1) a gateway point; (2) a vehicle point; and (3) a combined gateway-vehicle point. The 2-1 dimensional reduction algorithm is detailed in Algorithm I. The major steps of Algorithm I are as follows. First, nodes are grouped according to their X-axis coordinate; nodes that have the same X-axis coordinate belong to the same group σ_i, where $1 \leq i \leq \left\lceil \frac{n}{m+1} \right\rceil$, n is the total number of nodes on the street and m is the number of street lanes. These steps are accomplished in lines 1-5 (See Algorithm 1). Then, each group of nodes is assigned a representative point p_i , where $1 \leq i \leq \left\lceil \frac{n}{m+1} \right\rceil$.

Algorithm I. 2-1 Dimension Reduction

```
Input:  Graph G=(V,E) ,  Line l, n nodes.
Output: Representative points:$p_1, p_2, \ldots, p_i$ (i.e., $i = O(n)$)
Step 1: grouping of nodes of G according to their X-axis coordinate
  1. For  any node v and u  in G do
  2.    If [proj(v)==proj(u) then     //(see Equation 8)
  3.          Make a group $\sigma_i$  //insert u and v into the same group
  4.       End if
  5. End for
Step 2: Orthogonal projection of the nodes of each group onto  the X-axis line.
  6. For each group do
  7.    For each node $u$ in the group do
  8.          $p_i$ =Proj(u)    //  (see equation 8)
  9.    End for
  10.End for
Step 3:   Mark the points according to their category
  11.For each formed group do
  12.    If all nodes are gateways then
  13          Mark    $p_i$ as a vehicle
  14.    Else if all nodes are vehicles then
  15             Mark  $p_i$ as a  combined point(gateway and vehicle)
  16.    Else if the nodes are gateways and vehicles then
  17   Mark $p_i$ as a combined point (either gateway or vehicles
  18.   End if
  19. End for
```

20. Return the **set of $\boldsymbol{p_i}$** points

The point p_i is obtained using an orthogonal projection, on the X-axis, of any node of the group. If $e = (1,0)$ the unit vector in the direction of the X-axis and v_i = (a,b) a node that belongs to group σ_i , then the orthogonal projection p_i of v_i = (a,b) onto the X-axis is as follows:

$$\mathrm{p_i} = \mathrm{proj}(\mathrm{v_i}) = (\mathrm{a}, 0) \tag{8}$$

Then, we make use of three markups to obtain three categories of points. If all nodes in the group are vehicles, then the representative point is marked as a vehicle. If the nodes in the group are all gateways, then the point is marked as a gateway. If the group consists of gateways and vehicles, then the point is marked as a combined point. These steps are accomplished in lines 6-19 (See Algorithm I). Finally, we return the set of points in line 20.

5.4.4. Exact solution

In this section, we present the decision algorithm to solve the 1-dimensional GP problem. The resolution process is described in Algorithm II. The basic idea of the algorithm is to increase the radius r until covering all points (vehicles) using k intervals. Indeed, if we increase radius r, then the required number of gateways k will decrease. We start by an optimal radius which is equal to 1 hop (the transmission range). Then, we increase the radius r each time by 1 hop. The algorithm ends if it meets the required number of gateways k and returns radius r. The major steps of Algorithm II are as follows: (1) we initiate the radius of gateways to 1 in line 1. Then, we generate the coverage intervals $\mathrm{I_i}(\mathrm{r})$ (the interval center is a gateway representing point p_i; the length of the interval equals $2 * r$) of all points marked as gateways or combined points, in lines 2-7; (2) we sort the intervals according to their left endpoints $\mathrm{a_i}(\mathrm{r})$; this is accomplished in line 8; (3) we select the gateways as follows: In line 12, we select the leftmost endpoint in the sorted intervals set.

Algorithm II. Gateway Placement

```
Input: Set of $p_i$ points (Output of Algorithm I)
        Required number of gateways k.
Output: Radius r (minimum communication hops).
        A set of selected gateways locations.
1.  Initiate radius r=1
2.  For each gateway $p_i$ do
3.      $\mathrm{a_i(r)} = p_i - (r, 0)$ (See Equation 8)
4.      $\mathrm{b_i(r)} = p_i + (r, 0)$ (See Equation 8)
5.      $\mathrm{I_i(r)} = [\mathrm{a_i(r)}, \mathrm{b_i(r)}]$
6.  End for
7.  $\mathrm{I} = \{\mathrm{I_i(r)}\}$
8.  Sort intervals in $I$ according to the X-axis coordinate of the left endpoint $a_i$.
9.  $k(r) = 0$
10. While [$(k(r) \leq k)$ and (not all vehicles are covered)] do
11.     While $(\boldsymbol{I} \neq \emptyset)$
12.         Select the leftmost endpoint $\mathrm{a_i(r)}$ in the sorted $I$
13.         Mark its center $p_i$ as a selected gateway point
14.         $k(r) + +$
15.         Binary Search of any interval $\mathrm{I_i(r)}$ in $I$ that covers
            the selected gateway point $p_i$
16.         I=I\ {$\mathrm{I_i(r)}$}
17.     End while
18. End while
19. If [$(\boldsymbol{k(r)} \leq \boldsymbol{k})$] and (all vehicles are covered) then
20.     Return radius r and the selected gateways
21. Else
22.     r ++
23.     Go to step 2
24. End if
```

We mark its center as a selected gateway, in line 13. We increase the number of selected gateways k, in line 14; (4) in lines 15-16, we perform a binary search in the set of intervals *I* to find all intervals that cover the selected gateway center. If any, we remove that interval from intervals set *I*. These steps are briefly listed in line 15; and (5) in lines 19-24, we check whether the number of selected gateways k(r) is smaller than the predefined number of gateways k and all vehicle points are covered. If the response is no, we increase the radius r and repeat steps of lines 2-18; otherwise, we identify the gateways placement set and the minimum radius in line 20.

- *Proposition:* Algorithm II selects k(r) gateways and minimizes the length r of the path which is longest among all shortest paths in $O(n^2 * \log(n))$, where n is the total number of nodes along the street. Note that, a path is a route from a vehicle to its closest gateway.
- *Proof:* The number of gateways *k* is bounded by *n*. For each radius r, we sort the intervals, in line 8, which takes $O(n\log(n))$. Then, in line 10, we iteratively select at most $k = n$ gateways. Therefore, the complexity of this step is $O(n)$. For each selected gateway, we do binary search in line 15. The complexity of the binary search is $O(n\log(n))$. The complexity of lines 10-18 is $O(n^2 * \log(n))$. Therefore, the total running time of the decision algorithm is $O(n^2 * \log(n))$.
- *Proposition:* Algorithm II returns optimal radius (called r^*). Note that optimal radius means the minimum radius such that there exist *k* gateways of that radius with union covering *n* input points.
- *Proof:* To prove this, we suppose the proposition was false, i.e., let us assume that there exists an optimal radius r_{opt} , such that $r_{opt} < r^*$ and that there exist *k* gateways of that radius with union covering *n* input points. Let S be the set of input points. Let $\mathrm{d_{max}}$ be the maximum distance in terms of hops from a vehicle to its closest gateway; $d_{max} = max\left\lceil\frac{|x_i - x_j|}{Tr}\right\rceil$, where x_i is the X-axis value of a vehicle point and x_j is the X-axis value of a gateway point, $1 \le i \le n$, $1 \le j \le n$. It is clear that $r_{opt} \ge d_{max}$. Algorithm II increases the radius r each iteration by 1 hop. If the following conditions: 1) number of selected gateways $k(r)$ is upper bounded by k; and 2) all points in S are covered; are true, the algorithm returns r^*. Therefore, in case the number of selected gateways when $r = d_{max}$ is not greater than k, and all points in S are covered, then $\mathrm{r}^* = d_{max}$. However, we have already supposed that $r_{opt} < r^*$. As a result, $r_{opt} < d_{max}$ which

is not possible. This contradiction shows that $r_{opt} = r^*$. Now, in what follows we suppose $r_{opt} > d_{max}$ and $r > d_{max}$. As r increases, the endpoint $a_i(r)$ of an interval $I_i(r)$decreases (the endpoint point $b_i(r)$ increases) and the number of gateway points in the interval $I_i(r)$ increases. Thus, k(r) decreases only when the relative order of the endpoints $a_i(r)$ (or $b_i(r)$) and the gateway points p_i changes. When r increases, the binary search in line 15 of Algorithm II removes more gateway points from the interval of the selected gateway point. Consequently, the number of remained intervals in line 16 decreases and the number of selected gateways k(r) computed in line 14 decreases. Our goal is to find the minimum radius r^* such that $k(r^*)$ is the largest integer with $k(r^*) \leq k$ and covering all points in S. Since k(r) can decrease only when the radius increases, a straightforward way to find the radius r^* is to keep increasing radius r by 1 hop (line 22). For each iteration, we do a binary search (line15) and we remove intervals containing the selected gateway. In line 19, we evaluate if $k(r) \leq k$ and if all points in S are covered. If the condition is false, we increase r until the first time the condition is true. Finally, we return r^* in line 20. As we supposed, above, that $r_{opt} < r^*$. This means, $\exists\ r,$ such that $r < r^*$and $k(r) \leq k$ covering all input points. This is not possible because Algorithm II returns r^* the first time the two conditions are true). This contradiction concludes the proof and shows, as before, that $r^* = r_{opt}$. Therefore, Algorithm II returns optimal radius.

5.5. Gateway Discovery

In this section, we present the gateway discovery protocol. Each gateway periodically broadcasts advertisement messages to all vehicles located in its Ex-Range. In [31], we already proved the effectiveness of M-HRB protocol to ensure very high reliability for multi-hop emergency message dissemination in city environments. For this reason we make use of M-HRB to establish reliable paths between gateways and vehicles. As the vehicle can move in any direction to travel, this creates a rapid changing topology at any speed resulting in difficulties to handle the vehicular node mobility. Thus, M-HRB makes use of the vehicle location to select the forwarding node. The main idea of M-HRB is to ensure very high reliability for each hop. To achieve this, M-HRB estimates the reception quality of 802.11p wireless link in cells to select forwarding nodes locations [31]. Basically, M-HRB exploits periodic beacons to estimate the quality of 802.11p wireless link. Using this information, each hop, minimum possible forwarding locations are selected to enforce achieving very high reliability.

5.6. Performance Analysis

In this section, we evaluate the proposed RICS (GP with M-HRB). We run simulations using Omnet++ 4.3 and Sumo traffic simulator. Our C++ code uses Omnet++ as a discrete event simulator and Veins 2.0 for DSRC simulated components [2]. Our simulation scenario is composed of 4 km fragment of a real map street [131]. We configured Omnet++ to model the impact of both distance and obstacles (building and moving vehicles) on signal propagation.

Table 5.1 shows the simulation parameters. We use shell script to extract vehicles positions from Omnet++ and run Algorithm I and Algorithm II to select the required number of gateways k and fix the radius r. The number of gateways k is a function of the vehicles density; it varies from 5% to 15%. We did consider two simulation scenarios: (1) Scenario 1: In this scenario, the density assumes 80 vehicles/km (40 vehicles/lane/km); we vary the gateway penetration rate from 5% to 15% gateways; (2) Scenario 2: In this scenario, the density assumes 120 vehicles/km (60 vehicles/lane/km); we vary the gateways penetration rate from 5% to 15%. In both scenarios, each gateway generates an advertisement message at a rate of w messages/second.

Table 5.1. Simulation parameters

Simulation parameter	**Value**
Fading model	Rayleigh [102]
Transmission range (*Tr)*	250 meters [132]
Tx power	20 dBm
WM, Beacon length	292,72 bytes.
Vehicle density	80-120 cars/km
Reliability requirement r_{th}	0.97
Simulation duration	10 minutes
Vehicle speed Ve	10-50 km/hour
Number of street lanes m	2 lanes
Cell transit time T_s	0.2 seconds [31]
Update time period T_p	1 minute
Density collection period T_g	1 minute [133]
Advertisement period	1 second
Beacon period	0.1 second

We performed 5 simulation runs for a confidence interval of 95%. The performance parameters, we did consider in the evaluation of RICS, are: (1) Packet reception ratio (PRR): the average percentage of vehicles that receive the advertisement message; (2) Network load: it includes beacon overhead, advertisement/discovery transmissions and data retransmissions; and (3) Average propagation delay: the propagation delay represents the time it takes an advertisement/discovery message, sent by the source (gateway), to be received by vehicles in the advertisement/discovery area (see Table 5.2).

Table 5.2. Gateway discovery schemes

Category	**Advertisement/Discovery area**	**Advertisement/Discovery protocols**
GP + M-HRB	Ex-Range	M-HRB
Proactive [52]	All the network	CDS-based advertisement
Reactive [26]	All the network	PBR[26]
4-Hybrid [54]	4 hops	ODAM[134]+ CFB[135]
2-Hybrid [54]	2 Hops	ODAM[134]+ CFB[135]

To evaluate the effectiveness of the proposed RICS, we compare it with the following gateway discovery approaches: (1) Proactive approach [52], where the route to the gateway is CDS with the longest lifetime. To build CDS, the moving direction is the main mobility parameter to predict link lifetime between two neighboring vehicles; (2) Reactive approach [26], where the discovery protocol uses location and speed of vehicles to predict routes to the gateways; and (3) Hybrid approach [54], where the gateway discovery protocol uses the characteristics of vehicle movements (e.g.,speed and direction of movement) to predict the future behavior of vehicles, and to select the route with the longest lifetime to connect vehicles to the gateways. For the hybrid approach [54], we implemented two instances: (*i*) 2-Hybrid, where the size of the proactive area is 2, and *(ii)* 4-Hybrid, where the size of the proactive area is 4.

A. *Results*

Figure 5.3 shows the variation of radius r with gateways penetration rate. When the number of selected gateways increases, radius r decreases considerably. For example, when gateways penetration rate is 10%, the radius r is 3 hops against 9 hops when gateways penetration rate is 5. This can be explained by the fact that when gateway penetration rate is 5, the condition (covering all vehicles) in step 10 of Algorithm II is not fulfilled for values of r smaller than 9 hops. Thus, gateways increase their radius r (step 22), until covering all the vehicles.

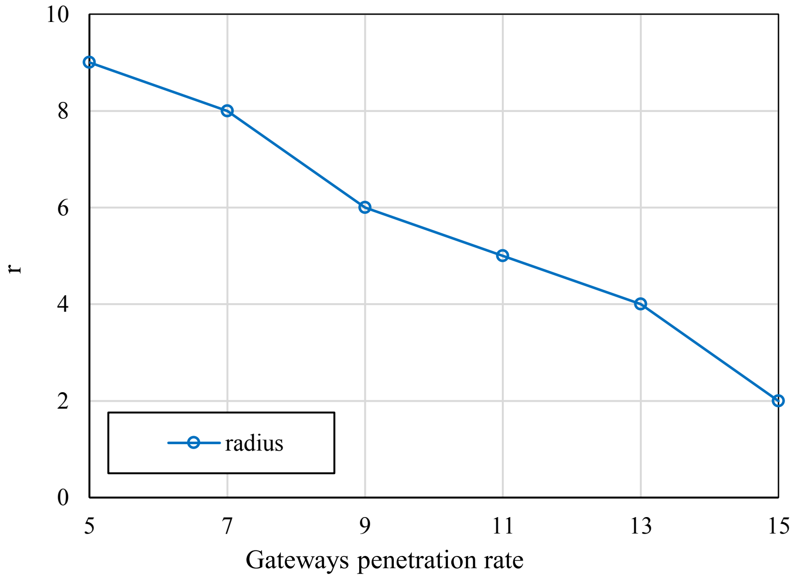
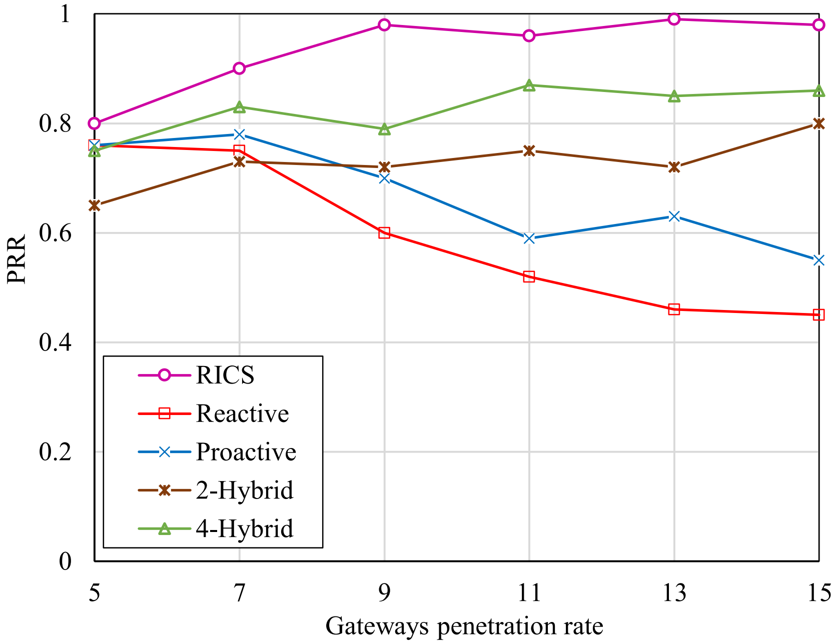
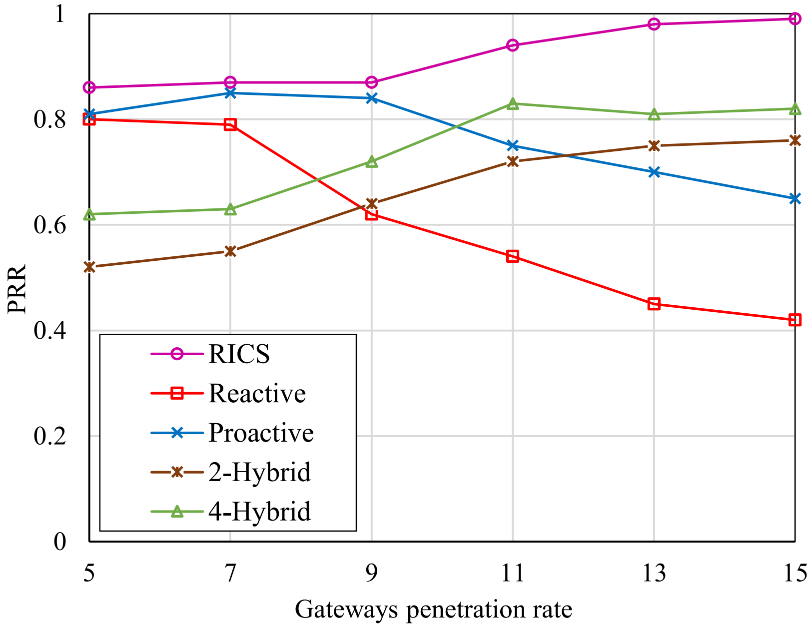


Figure 5.3. Variation of minimum communication hops

Figure 5.4(a) and Figure 5.4(b) show the variation of PRR with gateways penetration rate. For both densities (80 vehicles/kilometer and 120 vehicles/kilometer), when gateways penetration rate increases, we observe that our approach outperforms the other approaches. For example, PRR achieved by RICS is 100 percent when gateways penetration rate is higher than 10% and vehicles density is 120 vehicles/kilometer, against 81% scored by 4-Hybrid and 73 % scored by 2-Hybrid. This is due to the route establishment mode which is based on the highest route lifetime. In city environments (the wireless communication channel is very erroneous and lossy), the links between vehicles are unreliable resulting in high packet loss. The outperformance of RICS in terms of PRR is related to the reliability method in M-HRB; which, for each hop along the path, selects forwarders having high reception quality [31]. In contrast, the reactive approach ensures the lowest PRR (PRR is 40% when gateway penetration rate is 15% and vehicles density is 120 vehicles density). The poor performance of the reactive approach in terms of PRR is related to its route discovery method. More specifically, the routes are established based on the predicted lifetime of links between two vehicles, where speed of neighboring vehicles is a main link parameter. In city settings, with high channel loss due to random interference, the resulting paths are not reliable incurring high packet loss. The worst performance of the proactive approach (PRR is 63% when gateways penetration rate is 15% and the density is 120 vehicles/kilometer) is related to its CDS nodes selection mode.



(a)

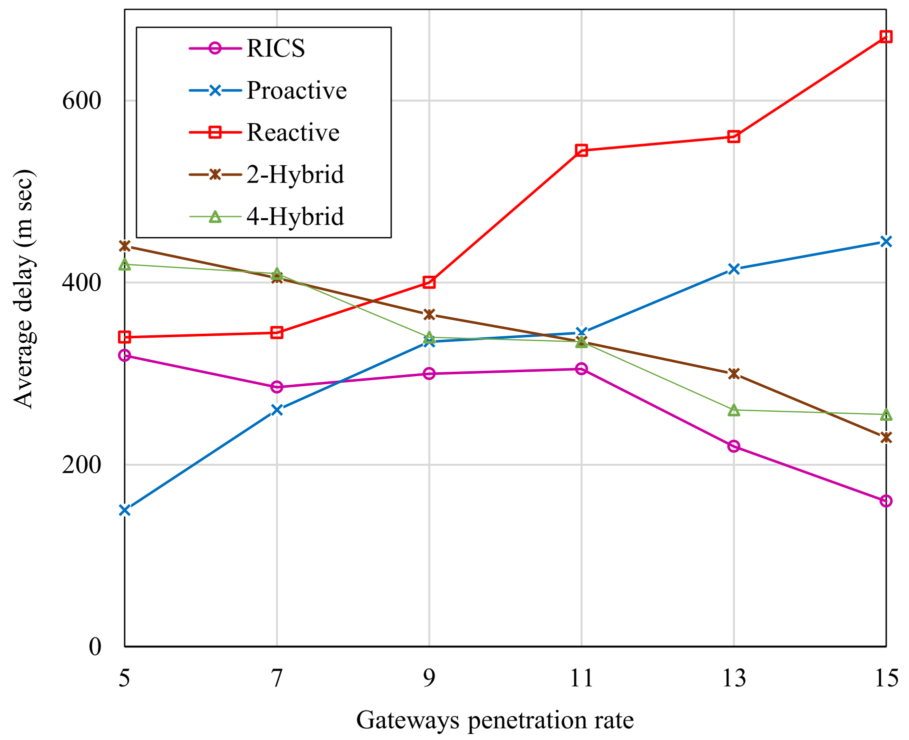


(b)

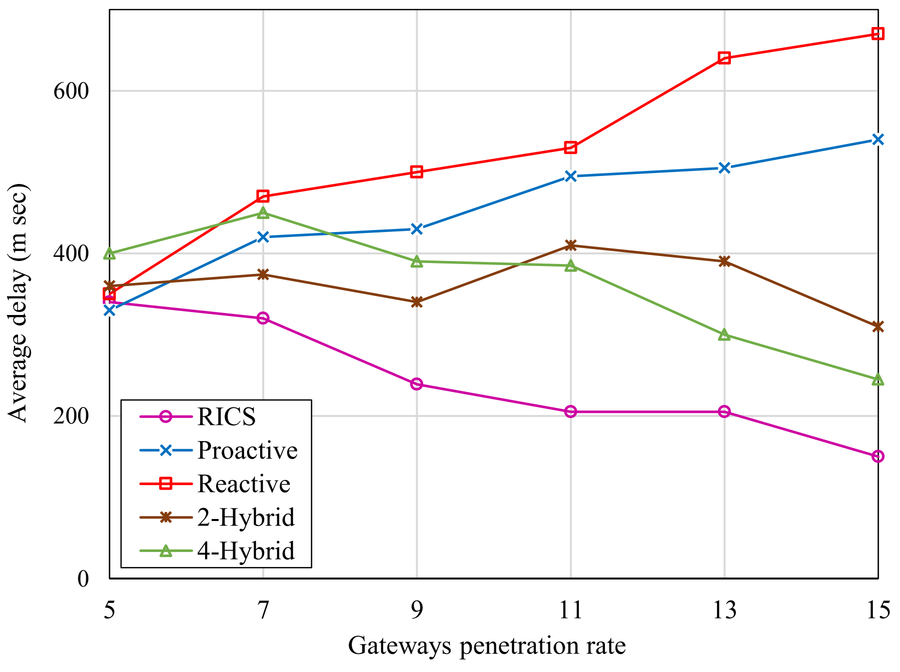
Figure 5.4. PRR vs. gateways penetration rate: (a) vehicle density: 80 vehicles/kilometer, (b) vehicle density: 120 vehicles/kilometer

More specifically, it selects forwarding nodes (forwarders) based on their link lifetime. In adverse network conditions (high vehicle density and high gateways penetration rate), CDS nodes may have low reception quality resulting in packet loss. This is because, the higher the gateway penetration rate, the higher the channel load (advertisement messages) and the higher the number of incurred collisions. In such situations, a message may be not delivered to CDS nodes. Unlike reactive and proactive approaches, M-HRB dynamically selects the appropriate forwarders (their number and their positions) based on their quality of wireless links.

Figure 5.5(a) and figure 5.5(b) show the variation of average delay with gateway penetration rate. As expected, RICS outperforms the other approaches. This is due to the fact that the GP problem of RICS selects gateways in a way to minimize the number of hops from vehicles to gateways. More specifically, the objective function (see Equation (2)) of GP minimizes the radius r. As the delay is proportional to the number of communication hops, RICS achieves low delay. Especially, when gateways penetration rate increases, the radius r of the Ex-Range decreases. In such a situation, RICS achieves very low delay. For example, the delay is 195 msec, when gateway penetration rate is 15% and vehicles density is 120 vehicles/kilometer. We also observe that the reactive approach ensures the highest delays for both densities. For example, the incurred delay is 650 msec when gateways penetration rate is 15% and vehicles density is 120 vehicles/kilometer). This increase in delay can be explained as follows: (1) when the number of vehicles in the network is very high, the number of gateway requests is high as well; and (2) when the gateways penetration rate increases, the total number of gateway replays and the number of transmitted gateway requests increase considerably. Thus, the network is congested resulting in dropping messages increasing the delay. The delay, with the proactive approach, increases with the number of gateways. This is because, in high density scenarios, links between established CDS nodes are unreliable resulting in links breakages. CDS maintenance and messages retransmissions incur high delay. Similarly, the delay, with the hybrid approaches, increases because routes break frequently in high density scenarios. In this case, nodes have to send more route requests resulting in higher delays.



(a)



(b)

Figure 5.5. Average delay: (a) 80 vehicles/kilometer, (b) 120 vehicles/kilometer

Figure 5.6 shows the variation of the network load with gateways penetration rate. When gateways penetration rate increases, the average network load incurred by our approach is almost uniform for the two network densities. This is expected; indeed, we increase the coverage radius of the gateways only if the condition in step 10 (all vehicles are covered) is not fulfilled. Thus, in almost all the cases, a vehicle is connected to only one gateway (except some vehicles in the border of the Ex-Ranges, in case Ex-Ranges intersect). However, the control overhead drastically increases with the increase of gateways in proactive gateway discovery, and with the increase of source nodes for reactive gateway discovery. The proactive approach results in very high network load when the gateway penetration rate increases. This is because, more gateways results in high average control overhead due to the creation and maintenance of CDSs over streets. The reactive approach incurs low overhead for small networks but it suffers from poor scalability. This is due to loss of route replay packets which are sent back to source nodes by the gateway using the chain of nodes in the gateway request packets. When the number of vehicles in the network is high and the number of gateway requests is high, the number of transmitted messages increases considerably. The number of route failures is high as well, requiring repair or reconstruction.

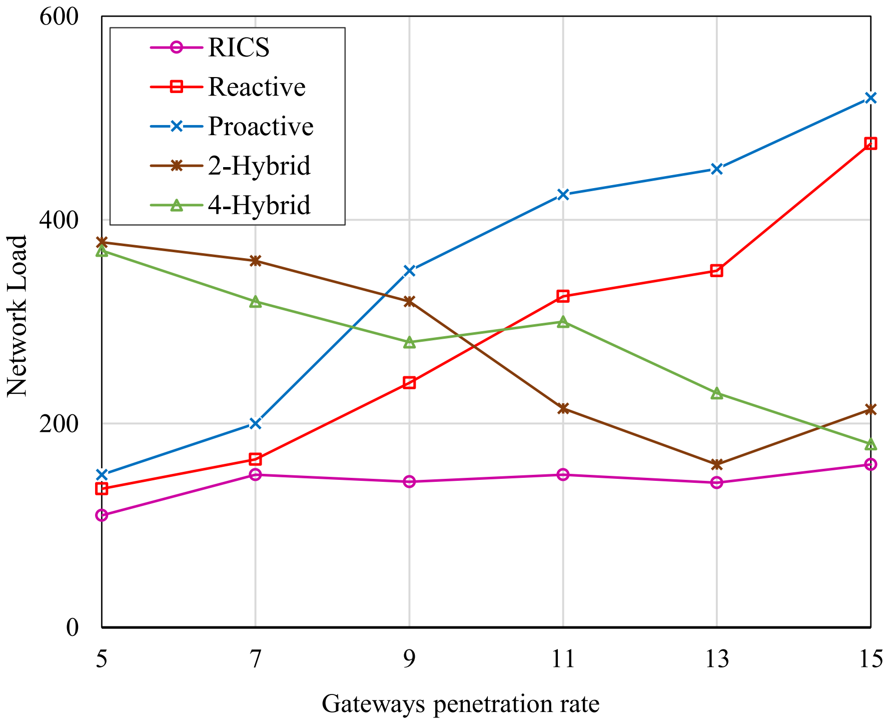


Figure 5.6. Network load vs gateways penetration rate

5.7. Conclusion

In this paper, we proposed an Internet access scheme to ensure multi-hop reliable paths between gateways and vehicles in city environments. Basically, internet gateways are deployed in a way that minimizes the communication hops subject to providing internet access to all vehicles. We modeled the gateway placement as a k-center optimisation problem. We make use of space dimension reduction to solve the problem in an exact time. Each gateway makes use of M-HRB scheme to establish communication paths. The main focus of this protocol is achieving reliability requirements of DSRC/802.11p-based broadcast. Numerical results show that, the proposed gateway placement algorithm together with the reliable gateway discovery protocol establish reliable communication paths in city environments.

Chapter 6
Conclusion

The chapter is organized as follows. Section 6.1 restates the research problem. Section 6.2 presents the thesis contributions. Section 6.3 presents perspectives and future work.

6.1. Background of the dissertation

Broadcast traffic is the cornerstone of vehicular applications. A broadcast message is not addressed to one specific vehicle, but to all vehicles positioned in one or more hops away from the transmitter. Indeed, to extend the reach of a broadcast message, multi-hop communications are used.

DSRC/802.11p based broadcast has the potential to provide low latency; however, it is defective in terms of reliability (reliability is defined as the probability of number of nodes in the geographic surrounding of a transmitter that can successfully receive the broadcast message) hindering the deployment IEEE DSRC/802.11p. Successful reception by every node within a specific surrounding cannot be guaranteed because there is no suitable way to acknowledge the reception of broadcast messages. Even if acknowledgement schemes are used, it will not be possible to ensure that every receiver gets the message.

In multi-hop, IEEE 802.11 MAC does not offer any specific support to improve reliability, apart from the naïve flooding scheme. However, such a solution may lead to the broadcast storm problem resulting in unreliability (i.e., high packet loss) and delayed communication. Conventionally, non-flooding schemes, that select forwarders, are the alternative. These schemes must compensate for the lack of reliability. However, existing schemes have several shortcomings.

Consequently, the development of novel schemes, that guarantee one-hop and multi-hop message dissemination reliability while satisfying short delay requirements of vehicular applications, is needed.

6.2. Contributions and Findings

The thesis consists of three contributions in the context of urban vehicular networks: (1) Reliable Emergency Message Dissemination scheme (REMD); (2) Bayesian networks and unipolar orthogonal Code based Reliable multi-hop Broadcast (BCRB); and (3) Reliable Internet access System (RICS).

REMD aims to ensure high broadcast reliability while preserving low end-to-end delay for safety applications, using message repetitions. The proposed cell concept provides fine-grained information about wireless channel conditions. REMD exploits periodic exchanged beacons to compute collision probability and signal power attenuation probability in each cell. By employing curve fitting, polynomial modeling and extrapolation, REMD estimates 802.11p link reception quality in cells. To compute optimal number of message repetitions, REMD proposes a Max-Min optimisation problem that ensures a predefined reliability requirements at each hop. A stochastic modeling approach is used to solve the Max-Min optimization problem. Indeed, the number of successful receivers, in the area covered by the sender, is computed from a Poisson Binomial distribution. Fast Fourrier Transform (FFT) enables an exact solution to the distribution in ($O(n \times log(n))$), where n is the number of cells. To combat hidden terminal problem (multi-user interference), Uni-Polar orthogonal codes are applied to the city street network. REMD also proposes a solution for efficient next-hop forwarders selection. REMD selects multiple forwarders with good link reception quality together with their locations at each hop. The forwarders use cooperative transmissions with the objective to achieve high reliability in intermediate hops. Simulation results show that REMD outperforms existing schemes in terms of reliability while still satisfying delay requirements of safety applications.

BCRB makes use of machine learning to accurately (compared to REMD) estimate 802.11p link reception quality in each cell. More specifically, BCRB exploits exchanged beacons to record training data from beacons reception state. Using this information, BCRB, based on Bayesian networks, infers 802.11p link reception quality in each cell. Using 802.11p link reception quality information, BCRB determines optimal number of broadcast repetitions in order to guarantee high message reception probability for each receiver in the area covered by the sender; it uses a binomial distribution applied to repeated transmissions at each receiver. Furthermore, BCRB assigns zero-correlated Uni-Polar Orthogonal Codes to adjacent road segments in order to cancel interference caused by hidden terminal problem. Like REMD, in multi-hop, BCRB carefully selects multiple forwarders and their locations. Forwarders of same hop cooperate with the objective to achieve high reliability in intermediate hops. Simulation results show that both BCRB and REMD successfully achieve high reliability in lossy channel.

BCRB outperforms REMD in terms of communication delay and network load. This makes BCRB a good emergency message dissemination scheme in urban environments.

RICS is an Internet access scheme that establishes multi-hop reliable paths between gateways and vehicles in city environments. Basically, internet gateways are deployed in a way that minimizes the number of communication hops subject to providing internet access to all vehicles. We modeled the gateway placement as a k-center optimisation problem. We make use of a space dimension reduction technique to solve the problem in $O(n^2 \times \log(n))$ exact time, where n is the number of vehicles. Each gateway makes use of BCRB to establish reliable communication paths in city environments.

6.3. Future work

In this section, we briefly present possible/few future work as a follow-up to this thesis:

(1) **A congestion control method for BCRB:**

In Chapter 4, we proposed BCRB which uses broadcast repetitions to ensure high reliability. Indeed, BCRB computes an optimal number of repetitions, according to channel conditions. In congested scenario (i.e., high number of street lanes and the traffic density on each congested lane is about 140veh/km), optimal repetitions may be high causing an overload of the network when coupled with exchanged beacons. It would be desirable for BCRB to perform well even in the presence of congestion. Therefore, a congestion control solution is required. A possible solution would be to: (a) make use of adaptive beacon rate (based on network conditions) in order to save bandwidth; and (b) propose a repetition cutting mechanism that prevents a sender from repeating messages if, for example, the variation in the reliability values (i.e., the difference value between reliability values of two successive repetitions) in smaller than a threshold value.

(2) A Bayesian network based beacon rate adaptation scheme:

Safety applications use two types of messages: (a) emergency (event driven) messages: they are generated when an event occurs (e.g., a car accident) and are disseminated in the network to notify vehicles of interest; and (b) beacons: they are periodic messages (broadcast) generated several times per second to exchange information with neighbors. In chapters 3 and 4, we proposed two emergency message dissemination schemes. Beacons are equally as important as emergency messages. This is because the dissemination strategy usually relies on information provided by beacons to choose forwarders, choose number of repetitions, etc. However, when the network density is high, beacons may cause network congestion resulting in performance degradation of safety applications. Therefore, a congestion control approach is required. A possible solution would be to use Bayesian network to estimate link reception quality at different locations. Using this information (link reception quality) as a metric, we control the beacon generation frequency and therefore reduce the effect of congestion.

(3) A distributed gateway placement approach of RICS:

In Chapter 5, we proposed an Internet access scheme, labeled RICS, which uses a centralized approach for gateways placement (i.e., In RICS, vehicles density information is transmitted according to the scheme in [122] to a central server, for each time period T_g (e.g., T_g =1 minute). Yet, a centralized approach for traffic estimation is characterized by longer response times, especially in big cities (longer time to exchange traffic information). Therefore, an extension to RICS is to develop a distributed gateway placement approach. A possible solution consists of using an online parallel approach which does not require vehicle density information but it is based on cooperative communication among gateways. Thus, a trade-off needs to be carefully computed to minimize overhead.

(4) RICS supports delay-constrained infotainment applications:

In Chapter 5, we proposed RICS which guarantees reliable paths to gateways. Several infotainment applications are delay-constraint. Here, we consider that communication delay depends on the number of communication hops. Even though, RICS aims to minimize communication delay, it does not ensure a communication delay that is smaller than a threshold. Therefore, an extension to RICS would be to propose a mechanism that guarantees requirement in terms of delay. A possible solution would be to model the gateway placement as a covering optimization problem with the objective to minimize number of gateways while ensuring the number of communication hops is smaller than a threshold value.

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