

UNIVERSITY OF CALIFORNIA

Los Angeles

**Using Heterogeneous Networks for Intersection Collision
Avoidance**

A dissertation submitted in partial satisfaction of the
requirements for the degree Doctor of Philosophy
in Computer Science

by

Lung-Chih Tung

2014

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ABSTRACT OF THE DISSERTATION

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Lung-Chih Tung

Doctor of Philosophy in Computer Science

University of California, Los Angeles, 2014

Professor Mario Gerla, Chair

Vehicular Ad-Hoc Network (VANET) is one of the most active research areas in ad hoc networks. In VANETs, each vehicle is equipped with wireless device so that it can communicate with other vehicles. With this capability, new applications targeting safety, entertainment, and better driving experience can be developed.

The most urgent applications that arise much attention are the vehicular safety applications. Most safety applications can be achieved by exchanging small data packets called beacons. Beacons contain the position information of vehicles. By analyzing the position information, a warning can be issued when a potential collision is identified.

However, some applications require warning messages to be disseminated multiple hops away, so a multiple hop data dissemination protocol is needed in these cases. To disseminate data efficiently, directional broadcast was proposed. The key idea is to select one relay node in each selected directions so that data can be propagated to all vehicles. However, it causes misclassification problem which results in inefficient and unreliable data propagation.

For intersection collision avoidance, new concerns need to be taken care of. In urban area, the wireless communication can be blocked by buildings around the corner. Previous research shows that the line-of-sight condition in urban area is not good enough for identifying potential collisions within sufficient time before impact. Therefore, a road side unit installed in the center of an intersection is necessary in order to rebroadcast beacons to vehicles around the intersection. This incurs additional cost of the deployment of VANET infrastructure.

The first part of this thesis explores the details of directional broadcast in terms of performance, and proposes a novel map-based directional broadcast protocol. We also incorporate a retransmission mechanism if transmission is regarded as failed to overcome the unreliable wireless communication. Store-carry-forward approach is used to increase the delivery ratio and efficiency. Moreover, we propose a solution to improve the safety of bicyclists using camera and DSRC. Simulations show that the map-based relay selection protocol can select relay nodes efficiently, and the retransmission combined with store-carry-forward approach increases delivery ratio significantly.

For intersection collision avoidance, the original plan of connected vehicle project includes the deployment of massive number of road-side units at intersections. Due to the cost, the deployment of road-side units has been indefinitely postponed. Without road-side units, data cannot be propagated well at intersections in urban area because the line-of-sight transmission could be blocked by buildings around the corner. Aiming on this, LTE has been proposed as an alternative to overcome this problem. We analyze and evaluate the possibility of using LTE for intersection collision avoidance service. Based on our study, LTE should be able to provide satisfactory delay and bandwidth for limited number of users. In order to improve the bandwidth usage, we propose a cluster architecture using both short range and long range communication technology. Meanwhile, a prioritization scheme can also be used to provide

service to users who need it most. We envision a world with safe and entertaining journey in the future with the popularity of VANET applications.

The dissertation of Lung-Chih Tung is approved.

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2014

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PUBLICATIONS

1. Lung-Chih Tung, Jorge Mena, Mario Gerla, Christoph Sommer, “A Cluster-Based Architecture for Intersection Collision Avoidance Using Heterogeneous Networks”, MedHocNet 2013, Ajaccio, Corsica, France
2. Lung-Chih Tung, You Lu, Mario Gerla, “Priority-Based Congestion Control Algorithm for Cross-Traffic Assistance on LTE Networks”, VTC 2013, Las Vegas, NV, USA
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4. Lung-Chih Tung, Mario Gerla, “RTMB/CTMB: A Collision Avoidance Scheme for VANET Broadcast”, WIVEC 2011, San Francisco, CA, USA
5. Lung-Chih Tung, Mario Gerla, “An Efficient Map-based Directional Broadcast Protocol for Urban VANETs”, VNC 2010, Jersey City, NJ, USA

6. Pei-Chun Cheng, Jui-Ting Weng, Lung-Chih Tung, Kevin C. Lee, Mario Gerla, Jerome Haerri, “GeoDTN+Nav: A Hybrid Geographic and DTN Routing with Navigation Assistance in Urban Vehicular Network”, MobiQuitous/ISVCS 2008, Trinity College Dublin, Ireland – Best Paper Award.

Chapter 1 Introduction

Intelligent transportation system (ITS) is a system dedicated to improve transportation safety and mobility. It comprises a wide range of wireless and wire communication technologies to disseminate traffic or management information to improve safety and productivity. Potential applications include but are not limited to collision avoidance, traffic incident management, and driving assistance service. ITS can be generally divided into intelligent infrastructure system and intelligent vehicle system [1]. Intelligent infrastructure system consists of the backbone management system such as transportation management center, and communication points to vehicles such as Road-Side Units (RSUs). Intelligent vehicle system is formed by vehicles equipped with wireless communication technology. These vehicles also compose Vehicle Ad-hoc NETworks (VANETs). Data can be disseminated between vehicles or between vehicles and road-side units to achieve emergency handling and efficient transportation.

To make VANET applications feasible, data need to be disseminated between vehicles efficiently and reliably. Variety of communication technologies can be used for this purpose. In general, three approaches can be used: distributed, centralized, and hybrid approach. Each approach uses one or more wireless communication technologies to achieve its goal. The wireless communication technologies include short range communication technologies such as Dedicated Short Range Communication (DSRC) and Wi-Fi, and long range communication technologies such as 3G cellular networks and 3GPP Long Term Evolution (LTE) project.

In the distributed approach, vehicles exchange data to each other via wireless communications such as DSRC or Wi-Fi. For efficient information dissemination between vehicles, directional broadcast was proposed for VANETs [2][3][4][5]. The basic idea is to

propagate information in the selected directions. To achieve this goal, each vehicle is equipped with global positioning system (GPS) which provides geographical location of vehicles. Each vehicle exchanges small packet (called beacon) containing position information periodically. The neighboring vehicles are divided into groups based on the relative position to the current vehicle, and one relay node is selected in each group. The farthest node is selected to minimize the number of hops during data dissemination.

The traditional directional broadcast protocols for VANETs suffer from mistakenly classifying vehicles and therefore are not able to select minimum number of relay nodes. More importantly, the line-of-sight propagation in urban area does not propagate well at intersections because the transmission could be blocked by buildings around the corner. The original plan of connected vehicle project [59] includes the deployment of massive number of road-side units. Due to the cost, it has been indefinitely postponed. Without RSUs, beacon transmissions are not reliable enough at intersections.

The second approach uses cellular networks as the communication media between vehicles. Vehicles connect to base stations, and data are forwarded by the gateways connected to base stations. It offers reliable communication at intersections in urban area as oppose to short range direct communication. The main cellular technology we focus in this dissertation is LTE due to its high throughout and low latency characters.

The problem of the second approach is whether the bandwidth of LTE could support the vehicle traffic in urban area. We investigate this problem by theoretic analysis and simulations. Our study shows the bandwidth of LTE may provide satisfactory performance in terms of delay and delivery rate with limited number of vehicles.

As a result, in this dissertation, we propose a third approach which uses both short range communication technology and cellular network communication technology. The short range communication technology can be used to form a cluster of vehicles, and the cellular network

communication technology can be used for the communication between clusters, delegated by each cluster head. We use this architecture on the intersection collision avoidance service with which vehicles can be warned before potential impact when approaching an intersection. Simulations show the hybrid approach offers a promising solution to vehicular safety applications.

1.1 Dedicated Short-Range Communication

1.1.1 DSRC Standards

DSRC includes multiple standards ranging from physical layer to application layer. For physical layer and media access layer (MAC) layer, DSRC utilizes IEEE 802.11p protocol, a modified version of IEEE 802.11 (WiFi) protocol with the amendment of Wireless Access for Vehicular Environment (WAVE). IEEE 802.11p is designed to be working under special condition in vehicular environment such as Doppler effects. In the middle between application layer and MAC layer, IEEE 1609 standard family are used, including IEEE 1609.2, IEEE 1609.3, and IEEE 1609.4. The layer right above the MAC layer is the MAC Sublayer Extension. It uses IEEE 1609.4 providing Channel Switching – a mechanism allowing a device operating on multiple DSRC channels efficiently. The Logical Link Control (LLC) Sublayer is on top of the MAC Sublayer Extension, using IEEE 802.2 protocol supplemented with the SubNetwork Access Protocol (SNAP). IEEE 1609.2 and 1609.3 are used in Network layer. IEEE 1609.3 provides network service including the WAVE Short Message Protocol (WSMP), while IEEE 1609.2 is used for security service. At the same time, DSRC also supports Internet Protocols – TCP/UDP for Transportation layer and IPv6 for Network Layer. Which one should be used – WSMP or TCP/UDP+IPv6 – depends on the application requirements. In general, WSMP is more bandwidth efficient so it is more suited to be used for safety applications such as collision

avoidance, while TCP/UDP+IPv6 can be used for non-safety applications. A message sublayer is also included in DSRC protocol stack which uses SAE J2735 and SAE J2945.1 standards [61][62][63][64][65][66].

1.1.2 DSRC Channels

The US Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz for DSRC, from 5.850 GHz to 5.925 GHz. The word “dedicated” is given because of the licensed bandwidth. There are seven channels in this band, each of which is 10 MHz wide. A 5 Mhz guard band is reserved in the beginning of this spectrum. Each channel can be designated as either Service CHannel (SCH) or Contorl CHannel (CCH). The MAC Sublayer Extension (defined in IEEE 1609.4 standard) manages one of more instances of the IEEE 802.11p MAC, maintaining a separate set of queues and state variables for each channel. It offers a channel switching technique for DSRC devices to communicate to each other at the same time. This could be challenging for a device with a single radio, because every device has to tune to the same channel at the same time. As a result, two concepts are proposed in IEEE 1609.4: control channel and time division. The control channel is used as a common place for every device to communicate to each other. For a single-radio device, time division allows it to switch between SCHs and the CCH. It requires every device to be time synchronized, for example, each device is synchronized based on Universal Coordinated Time (UTC), which is assumed to be accessed through GPS device.

IEEE 1609.4 defines “frame” for time division. Each frame is by default 100 ms. The first half of the frame is a CCH slot, which is used for accessing CCH. The last half of the frame is a SCH slot, which is used for accessing SCH. Each slot is 50 ms long, including a 4 ms guard interval in the beginning of the slot. When tuned to SCH, a device may receive WAVE Service Advertisement (WSA, defined in IEEE 1609.3). WSA contains information about the

services offered in the area, and the SCHs on which they are transmitted. A device hears the WSA may decide to switch to the SCH in SCH slot. It may also stay in the CCH during the SCH slot because there is no WSA or it is not interested in any service available [64]. The U.S. FCC has designated Service Channel 172 “exclusively for vehicle-to-vehicle safety communications for accident avoidance and mitigation, and safety of life and property applications”[60]. You can image that many stakeholder will want to use SCH 172 for their applications. It requires carefully design and government regulations to keep balance of the congestion control of the SCH.

1.1.3 DSRC at Intersections

One major goal of DSRC is to provide reliable communication between vehicles. The communication of DSRC is usually assumed to be line-of-sight communication. While DSRC may offer partial non-line-of-sight communication, it is not reliable and should not be a valid assumption for safety applications [34]. This is especially true in urban area in which buildings located around intersections is a common scene. Therefore, the connected vehicle research [59] conducted by U.S. Department of Transportation requires the deployment of RSUs along the road and around intersections. By connecting to infrastructure through RSUs, safety messages can be propagated well around intersections.

The connected vehicle test-bed shows evidence of prove of concept of safety applications using DSRC. There are 10 vehicles equipped with onboard units including DSRC radios for testing purpose. The test-bed includes the deployment of 55 RSUs along interstate highway and arterial roadways within a typical suburban area near Detroit. All RSUs connect to a backend data center offering data such as traffic or weather information.

However, due to the cost, the country-wide deployment of RSUs has been indefinitely postponed. Without RSUs, beacons do not propagate well at intersections. Other wireless

communication offering better non-line-of-sight communication may be used to assist collision avoidance around intersections.

1.2 Data Dissemination Using DSRC

The ITS researches done by U.S. Department of Transportation shows several potential DSRC safety applications [72]:

- Blind spot warnings
- Forward collision warnings
- Emergency brake warnings
- Intersection collision avoidance
- Do not pass warnings
- Approaching emergency vehicle warnings

These applications require each vehicle equipped with wireless device to regularly broadcast beacon messages containing basic state information of the vehicle. A neighbor vehicle receiving the beacon can analyze the data in the beacon and find out potential dangers. For example, a car taking emergency brake ahead can be identified by the rapidly dropped speed information in beacons. If a danger is identified, a warning will be informed to drivers to prevent future accident.

Although the potential hazard can be identified by analyzing data in beacons, to make better driving experience, it is suggested that warning messages can be propagated to vehicles around. For example, if a forward collision warning can be delivered multiple hops away, the cars behind can take actions such as changing lanes or taking a detour to avoid upcoming congestion. Moreover, for certain applications such as approaching emergency vehicle warning, the

warnings needs to be delivered multiple hops away to get better results. A multi-hop data dissemination protocol is needed in this case. The DSRC standards do not propose any multi-hop protocol nor define which application should use multi-hop data dissemination. It is left for VANET researchers to add this part of regulations in the future.

1.2.1 Directional broadcast

Flooding is used to disseminate data traditionally, but it causes the well-known broadcast storm problem [21][22][27]. In VANETs, directional broadcast was proposed to alleviate this problem. The basic idea is to broadcast data in the selected directions. In this approach, each node exchanges beacon messages with neighbors to get their position information every beacon update period. Based on this information, neighboring vehicles can be classified into several groups based on the relative position and only the farthest node in each group is selected. The directional broadcast approach improves bandwidth utilization by limiting broadcasting in the selected directions, and maintains comparable reliability as flooding.

Directional broadcast improves the bandwidth utilization in comparison to flooding, but it does not provide good enough efficiency in urban environment. For example, vehicles in other lanes could be mistakenly classified in different groups (Figure 1-1). This causes redundant transmissions because multiple nodes (up to 6 nodes in Figure 1-1) on the same road will be selected as the relay nodes. It could make the performance degrade seriously when node density is high (e.g., vehicles on highways during rush hour).

In the data dissemination process, some factors, such as collisions, interference, may affect the performance of data dissemination protocols. Furthermore, because of the obstacles in the urban area, the inter-vehicle communication is not reliable. Selected relays could be blocked by the buildings around the corner when a node is near an intersection. Since it is common to have buildings in the urban area, the effect of obstacles is non-negligible.

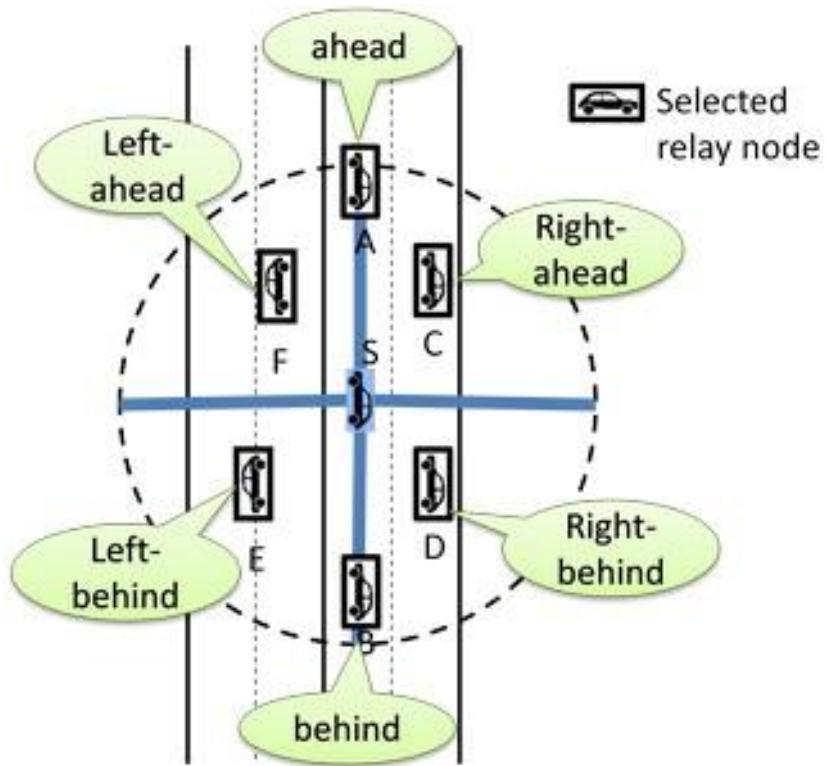


FIGURE 1-1 For node S, the neighbor nodes are divided into 6 groups, and one relay node is selected in each group. It leads to redundant relay selection and is not very efficient.

Last but not the least, because of the rapidly-changed network topology, the intermittent network dis-connectivity should be dealt by VANET data dissemination protocols.

1.2.2 Opportunistic Forwarding

Exchanging beacons regularly may cause network congestion if node density is high. In order to eliminate the beacon-exchange overhead, the opportunistic forwarding approach [3][4] was proposed. In this approach, the control of rebroadcast shifts from senders to receivers. Instead of sending beacons periodically, the sender attaches its position information along with data and broadcast it. Upon receiving the message, each receiver sets up a timer with the expiration time inversely proportional to the inter-vehicle distance. The timer of the farthest

node will expire first, and thus it will rebroadcast the message first. Other nodes hearing the duplicate message broadcast by the farthest node will stop their timers and cancel their retransmissions.

The opportunistic forwarding approach offers a simple yet effective way of VANET broadcast. It avoids the problem of inaccurate beacon messages. However, in order to disseminate data towards all directions at intersections, it uses the same vehicle classification method as beacon-based approach and thus it does not solve the misclassification problem [4]. Vehicles in other lanes or a curve road will still be classified in different groups, and the problem in intersections still remains. For example, in Figure 1-2, the node B will rebroadcast messages received from node S because it is the farthest one. Node A will cancel its retransmission after it hears the duplicate message broadcast by B. Node C will not be able to

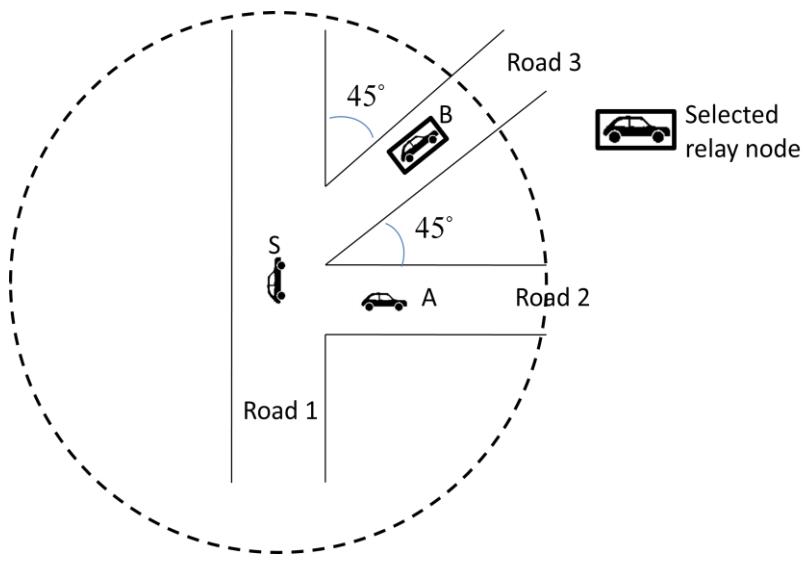


FIGURE 1-2 For node s, node A and B are classified in the same group because the angle between road 2 and road 3 is small. The propagation may stop on road 2 because only node B is selected as the relay node.

receive this message from node A, which causes propagation stops on road 2.

1.2.3 Map-based Directional Broadcast Protocol

Due to the drawbacks of data dissemination methods mentioned above, we aim to design a reliable and efficient VANET broadcast protocol. Based on the observation that node topology is constraint by road, it is a better strategy to use the road information for selecting relays. Our map-based relay selection utilizes the knowledge of road topology to classify vehicles, and thus avoids misclassification of neighbors. Meanwhile, when a node is near an intersection, our protocol selects relay nodes either inside the intersection region, or around the intersection, since nodes in or around intersections have the best line-of-sight to each road segments. Our protocol tends to utilize vehicles stopping at intersections (e.g., waiting for traffic lights) to disseminate data. It does not require repeaters at intersections and thus reduces deployment cost.

We also incorporate a retransmission mechanism if transmission is regarded as failed to overcome the unreliable wireless communication. Moreover, we use the store-carry-forward approach to increase the delivery ratio and efficiency. Simulations show that the map-based relay selection protocol can select relay nodes efficiently, and the retransmission combined with store-carry-forward approach increases delivery ratio significantly.

Another important issue in modern society is the safety of bicyclists. Most bicycle-car crashes happen at intersections. The main reason for these crashes is because the line-of-sight range around intersections is limited. The vision of car drivers can be blocked easily by buildings or large vehicles. In this dissertation, we discuss cases of bicycle-car crashes and propose a solution using DSRC devices and cameras. We assume a vision recognition algorithm is applied to detect bicycles with cameras installed on vehicles. The position information of bicycles then is broadcast to other cars using DSRC. Our map based directional

broadcast protocol is used to disseminate data at intersections. In this way, some cars become the “eyes” of other cars, increasing the perception range of drivers. By knowing the position of bicycles, the collision of car and bicycles at intersections can be prevented.

1.3 Challenges for Intersection Collision Avoidance

DSRC offers short latency needed for active safety protection. The communication of DSRC is usually assumed to be line-of-sight connection. This assumption may not hold in urban environment because buildings around the corner could block the wireless communication. Typically a warning should be issued to a driver 3 seconds before collision. Assuming two

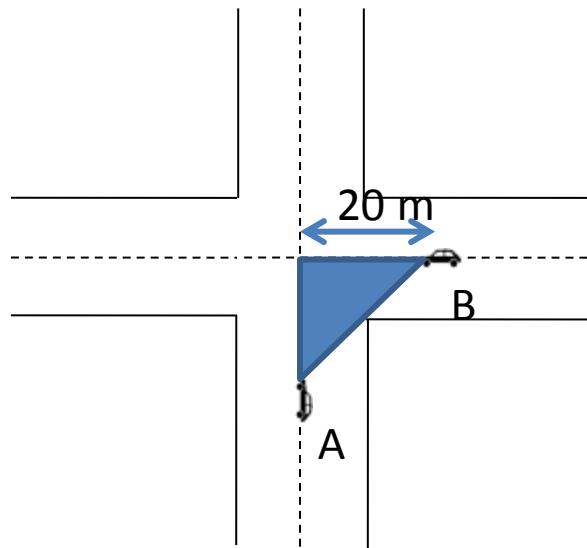


FIGURE 1-3 Assume car A and B are moving at 50 km/hour, and the road width is 20 m. The first point A and B can recognize each other is when they are 20 meters away from the intersection, which is not good enough for warnings to be issued 3 seconds before impact.

vehicles are moving at 50 km/hour, 3 second moving distance is roughly 42 meters. In [73], the authors analyzed the intersection structure using real city map (city of Munich) and building structure. The results show that if two cars are moving at 50 km/hour, only 20% of intersection can provide sufficient line-of-sight condition in order to identify a potential collision 3 seconds before impact. For intersection collision avoidance service, the safety of drivers cannot be guaranteed with the line-of-sight condition in urban environment.

Due to these reasons, LTE is proposed as an alternative to DSRC. Unlike the direct point to point transmissions in DSRC, the communications using LTE are controlled by base stations. Because base stations are usually mounted on the top of the buildings, LTE excels DSRC on the coverage in the urban area. This is especially useful for certain applications such as intersection collision avoidance service, when the communications of DSRC could be blocked around intersections.

However, it is not clear if the LTE bandwidth can support the beacon traffic. The state of art technology, LTE, offers as high as 50 Mbps uplink data rate and 100 Mbps downlink data rate. It can be operated on 1.4 – 20 MHz bandwidth. For intersection collision avoidance, the amount of traffic generated by beacons can be determined by a number of factors: the cell size, the number of intersection per cell, the number of vehicles per intersection per cell, the size of CAM, and the transmission interval. The cell size in LTE can be up to tens of kilometers. Assuming a typical cell size of 5km is used, and there are 10 intersections in a cell, 50 vehicles at each intersection, 5,000 beacons are generated per second if each vehicle transmits beacons at 10 Hz. We explore the possibility of using LTE for vehicular safety applications by both theoretical analysis and simulations. We propose a cluster based architecture for intersection collision avoidance service using both Wi-Fi and LTE technology. We discuss the applicability to prioritize users for cross-traffic assistance in order to fit the bandwidth requirement, while

satisfying the application needs. Our study shows the using heterogeneous networks offers satisfactory performance for VANET safety applications.

1.4 Dissertation Summary

The first part of this dissertation focuses on data dissemination protocols on VANETs. In Chapter 2, we propose an efficient broadcast protocol for VANETs using DSRC and road information. The road information we use is the road segment ID that will be transmitted in beacons. Based on this information, we avoid classifying vehicles into wrong categories so as to select minimum number of relay nodes and thus improve efficiency. In Chapter 3, we extend our broadcast protocol by handling network dis-connectivity and adding data retransmission mechanism. In this way, our directional broadcast protocol provides a promising solution to high mobility of VANETs while keeping the efficiency. In Chapter 4, a bicycle-vehicle collision avoidance service at intersections is proposed using DSRC and camera.

The second part of this thesis explores the possibility of using heterogeneous networks for real VANET application. The application that we focus on is the intersection collision avoidance service. 3GPP Long Term Evolution (LTE) offers high through and low latency, and thus has been proposed as an alternative to DSRC. However, it is not clear if the current state of LTE could offer sufficient bandwidth to support VANET applications. In Chapter 5, we estimate the number of users can be supported by LTE given various bandwidth configurations. It shows a theoretical view of bandwidth estimation. In Chapter 6, we evaluate the LTE bandwidth capability by conducting simulations using Network Simulator 3 (NS3) with LTE module. Different scenarios and protocols are evaluated and compared in this chapter. The simulation shows the current LTE may provide satisfactory performance for limited number of users. Therefore, in Chapter 7, we propose a cluster algorithm using both short range

communication such as Wi-Fi and LTE to alleviate bandwidth requirement. Wi-Fi is used for cluster creation and maintenance while LTE is used for cluster-to-cluster communication delegated by cluster heads. Moreover, we propose a priority-based congestion control algorithm for intersection collision avoidance service in order to serve users who need the service most. Different prioritization schemes are discussed and evaluated in Chapter 8.

Chapter 2 An Efficient Map-based Directional Broadcast Protocol for Urban VANETs

2.1 Introduction

The major challenge of traditional directional broadcast protocols is their efficiency: grouping vehicles based on the angles may lead to *misclassification*, which makes data propagation unreliable and inefficient. Misclassification can happen in an intersection or in a single road. In an intersection, vehicles on two roads could be classified in the same group if the angle between these two roads is small, as shown in Figure 2-1 (road 2 and road 3). If only the farthest node is selected for each group, the propagation could stop on one of these two roads. In addition, vehicles on the same road could be mistakenly classified in different groups in a straight or a curve road (Figure 2-2). This causes redundant transmissions because several nodes on the same road will be selected as the relay nodes. When node density is high (e.g., during rush hour on a highway), this problem could cause serious performance degradation.

Moreover, due to obstacles in the urban area, the inter-vehicle communication at an intersection is unreliable. The communication could be easily blocked by the buildings around the corner when the transmission starts (Figure 2-3). For the sake of reliability, selecting relay nodes near an intersection should be based on the line-of-sight rather than distance.

Due to the above reasons, we propose ERD – an Efficient Map-based Directional broadcast protocol for urban VANETs. With the help of GPS navigation system, our protocol groups vehicles based on which road segments they reside. Vehicles can be grouped correctly when they are on a straight road, curve road, or near an intersection. When a node is near an

intersection, nodes which offer better line-of-sight are selected. In this way, our protocol is able to propagate data toward selected directions, and avoid unnecessary retransmissions. Simulations show our protocol improve bandwidth utilization while keeping the same level of reliability as existing protocols.

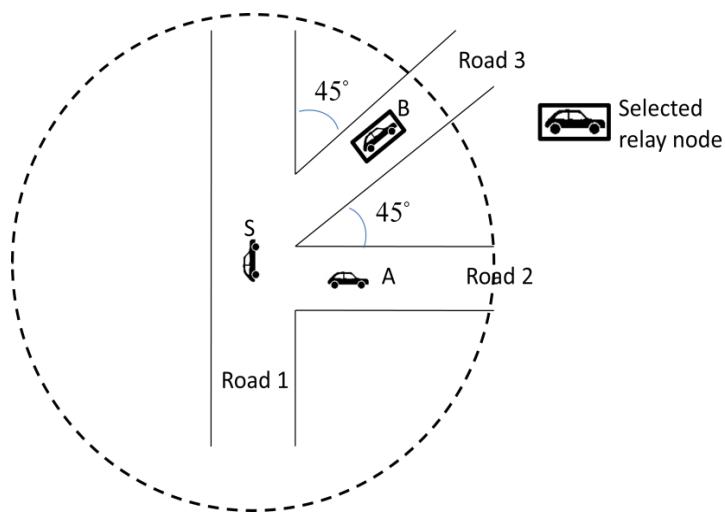
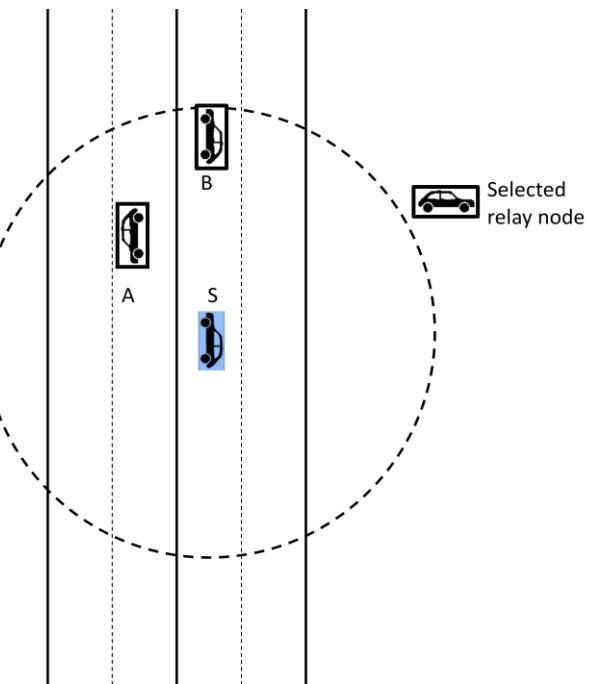
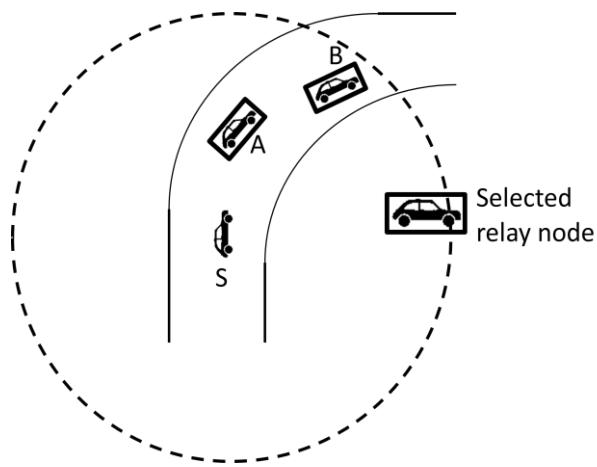


FIGURE 2-1 For node s, node A and B are classified in the same group because the angle between road 2 and road 3 is small. The propagation could stop on road 2 because only node B will rebroadcast packets.



(A) misclassification in a straight road



(B) misclassification in a curve road

FIGURE 2-2 For node s, node A and B are classified in different groups and both are selected as the relay nodes. In fact, only B needs to be selected in each case.

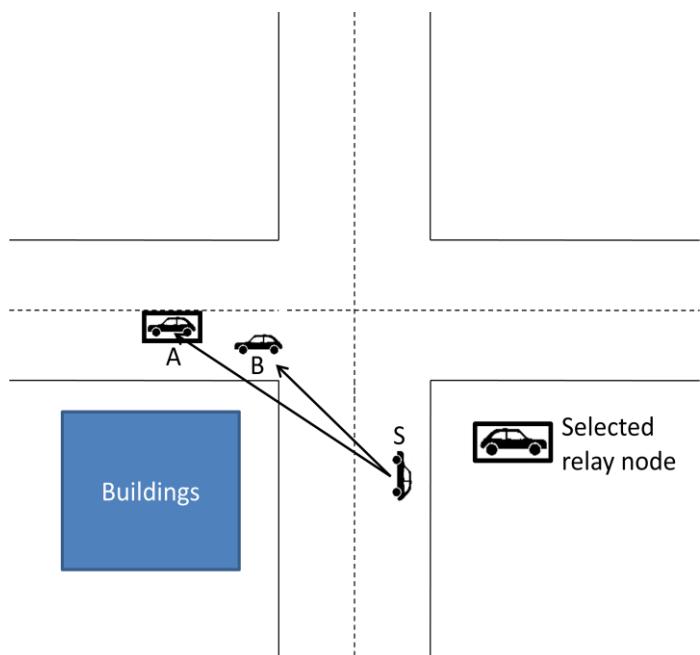


FIGURE 2-3 For node s, node A is selected as the relay node. However, the radio communication could be blocked by the building when the transmission starts. In contrast, node B offers better line-of-sight even if it is closer than A.

2.1.1 Broadcast protocols

Broadcast has been widely used for data dissemination in MANET. However, blind broadcast suffers from redundant transmissions, especially when node density is high. This is known as *broadcast storm problem* [27]. As a result, many researches based on blind broadcast have been proposed to improve performance by pruning redundant packet transmissions. In [21][22], the authors use neighborhood and history information to reduce redundant packets. H. Lim et al. propose *dominant pruning* [21], in which the sender selects the adjacent nodes that should relay the packets, and nodes exchange this information with nodes within 2 hops. In [22], A. Qayyum et al. propose *multipoint relay*, in which each node computes its own set of relay nodes. It achieves maximum performance by selecting an optimal set of relay nodes.

In [2][5], directional broadcast is proposed to improve bandwidth utilization. M. Sun et al. proposed Vector-based TRAcking Detection (V-TRADE) and History-enhanced Vector-based TRAcking Detection (HV-TRADE) protocol which considers vehicles' moving directions when selecting relay nodes [2]. Neighboring vehicles are categorized into five groups: *same road same direction ahead*, *same road same direction behind*, *same road opposite direction ahead*, *same road opposite direction behind*, and *different road*. After that, the sender selects the farthest node for each group to broadcast messages. It improves bandwidth utilization while maintaining the same level of reachability as the traditional broadcast protocols by limiting propagation in the selected directions. However, it classifies all vehicles on different roads as the same group and uses all of them to broadcast packets, and thus causes broadcast storm problem at intersections. In [5], the authors presented a new Reliable Broadcast routing scheme based on Mobility Prediction (RB-MP). RB-MP achieves reliability by calculating a *prediction holding time* (PHT) based on the relative speed and moving direction. The node with larger PHT should stay in the transmission range longer. It divides the neighbors into three sets: *same road ahead*, *same road behind*, and *different road* and selects the nodes with the biggest PHT

in each set as the relay node. It may not be able to broadcast packets to all other roads at intersections by classifying all nodes on different roads in the same group.

To deal with the broadcast problem at intersections, Da Li et al. propose a directional broadcast protocol by using directional antennas called Efficient Directional Broadcast (EDB) [3]. At an intersection, a directional repeater is installed which is used to forward messages to vehicles on different road segments attached to the intersection. Because the repeater has the best line-of-sight to the road segments, it is always forwarding the packet immediately to the different road segments after receiving the packet. The main drawback is that it requires the deployment of repeaters at intersections which induces high deployment cost. In [4], the authors propose a Reliable Broadcast considering Fragmentation and Intersection (RB-FI). It classifies vehicles on different roads at the intersection and limit broadcast effects to vehicles in the same group. All neighbor vehicles are classified into six groups according to the angles between them and the sender. Moreover, it uses store-and-forward approach to overcome network partition problem. However, it still suffers misclassification problem by classifying vehicles according to angels.

2.1.2 GPS navigation system

GPS navigation system offers a convenient way to identify routes to destinations; making driving easier and more comfortable. In general, a GPS navigation system contains three parts: a GPS receiver, a digital map, and a map matching mechanism. A GPS receiver provides the geo-position to drivers by communicating to satellites. A digital map stores the road topology and geo-coordinates, and related road information such as locations of restaurant, gas station, etc. A map matching mechanism can map the location given by the GPS receiver to a specific point on the digital map. For example, to identify on which road a vehicle is running, the map matching mechanism can map the point given by GPS receiver to the map, and compute the

closest road to the point. To improve the accuracy, if two consecutive points which represent the motion of vehicle are given, the line formed by these points can be mapped to the map and the angle between the line and the closest road on the map can be computed. If the angle is less than a threshold, the vehicle is regarded as on that road [13].

In this chapter, we make several definitions of road topology. A road segment is defined by the area between two intersections. An intersection itself is also a road segment. To support our protocol, the digital map needs to give each road segment an identity and store the information of intersection. This can be done during the construction of map. For example, the TIGER map [14] record type 1 (RT1) and record type 2 (RT2) offered by U.S. Census Bureau can be used to construct a digital map. RT1 contains the information of road, such as name, type, direction, start and end point. RT2 contains the information of the middle points of a road (Figure 2-4). Therefore, a start or end point can be identified as an intersection during construction if it is connected by another road, and each road segment can be given a road ID.

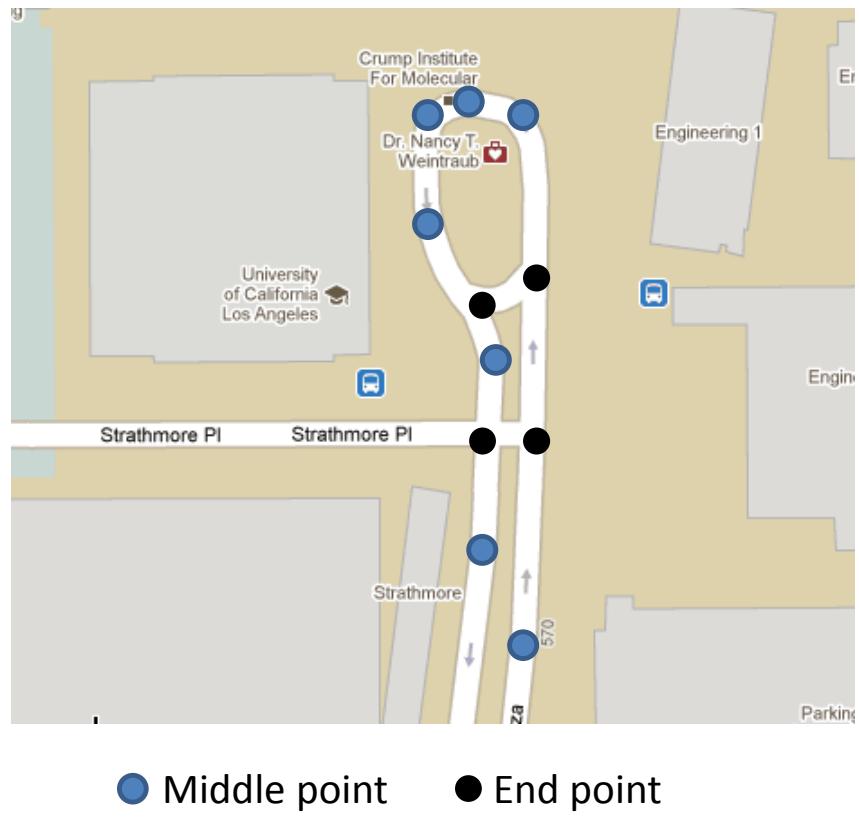


FIGURE 2-4 Constructed road graph from tiger map

2.2 Proposed Protocol

2.2.1 Assumptions

Our protocol makes the following assumptions. We assume that each vehicle is equipped with the GPS navigation system. Our protocol retrieves the following information from GPS navigation system: position, moving direction, a unique identifier of each road segment, and a flag indicating whether the current vehicle is in an intersection.

2.2.2 Beacon Message Format and Neighbor List Structure

Each vehicle broadcasts beacon messages periodically. A beacon message contains the following information:

TABLE 2-1 BEACON MESSAGE FORMAT

ID	Road ID	Position	IsIntersection
32 bits	32 bits	128 bits	1 bit

- ID: node identity.
- Road ID: road segment identity.
- Position: the position of node in (x, y) format. (x, y) is the GPS coordinate.
- IsIntersection: this field indicates if this node is in an intersection.

While a vehicle receives a beacon message from a neighbor, it creates a record for a new neighbor, or updates an existing record. Each field of a record can be taken directly from beacon message such as position, road ID, or after computation such as distance. A neighbor list is particularly designed to support our approach with the following data structure maintained in each node:

$<ID, Road ID, R-Position, Dist, IsIntersection, Selected, timestamp>$

Here we only explain the fields different from those in beacon messages:

- R-Position: the relative position of a neighbor with respect to the current node. It is the vector from the current node position to the neighbor.
- Dist: the inter-vehicle distance.
- Selected: this field indicates if a neighbor is selected as the relay node.
- Timestamp: the time this record has been created or updated. If a record has not been updated in one beacon update period (BUP), it will be deleted from the neighbor list.

2.2.3 Relay Node Selection

Before elaborating our relay node selection procedure, we define several terminologies first:

- *Forward nodes (\mathcal{F})*: nodes ahead of the current vehicle.
- *Backward nodes (\mathcal{B})*: nodes behind the current vehicle. Forward node and backward nodes are determined by the angle between the moving direction M of the current vehicle and the R-Position of a neighbor. Vehicle B is in front of A if

$$|\angle(M_A, R\text{-Position}_{AB})| \leq 90^\circ \quad (2.1)$$

otherwise B is behind A.

Upon receiving a beacon message, the relay node selection procedure begins. It first determines if the current node is in an intersection by checking *IsIntersection*. If yes, the procedure goes to the “*node in an intersection case*”. Otherwise it applies the following steps for forward and backward nodes respectively. For forward/backward nodes, the selection procedure checks if the current node is on a single road or near an intersection. This can be done by comparing the road ID of the current node and the road IDs of its neighbors. If all

road IDs are the same, it means the current node is on a single road and the procedure goes to the “*single road case*”, otherwise it goes to the “*node near an intersection case*”. For illustration purpose, we first elaborate the “*single road case*”, followed by the “*node near an intersection*” case. We regard “*node in an intersection*” as a special case of the *single road case* and explain it at last since they use the same rule to select relay nodes.

In the *single road case*, a node with the longest distance is selected. Note that the *single road case* also applies to a curve road. For nodes on a curvature, all nodes will have the same road ID and thus the *single road case* is applied. As a result, only one node is selected for the forward nodes and backward nodes respectively.

If one of the neighbors is in an intersection or on another road segment, the relay node selection procedure goes to the “*node near intersection case*”. The procedure selects it as the relay node and skips all other nodes if it is in an intersection since nodes in intersections have the best line-of-sight toward other road segments. If there are multiple nodes in the intersection, any one of them can be selected. If there is no node in the intersection, the procedure selects relay nodes for each road segments individually. A node N is selected if

$$\begin{cases} N \in \mathcal{F} \text{ and } N \text{ has } \min(|\angle(M, R\text{-Position})|) \\ \quad \text{or} \\ N \in \mathcal{B} \text{ and } N \text{ has } \max(|\angle(M, R\text{-Position})|) \end{cases} \quad (2.2)$$

where M is the moving direction of the current vehicle. In this way, we select relay nodes reliably at an intersection.

Figure 2-5 illustrates an example of relay node selection at an intersection. In Figure 2-5, node S, H and I are on the same road segment. Node A, B and C, node D and E, node F and G are on the other three road segments respectively. For forward nodes of S, there is no node in

the intersection so the selection procedure selects relay node for each road segment. Node A, D and F are selected since they have better line-of-sight. For backward nodes, node H is selected as the backward relay node because it is farther than node I.

A special case is that the current node itself is in the intersection. In this case, the relay node selection procedure groups vehicles according to road ID except the road where itself resides, and selects the relay node for each group individually. A node with longest distance will be selected.

As we can see above, our selection procedure select relay nodes efficiently and reliably. The rationale of our relay selection is that (1) our protocol selects one relay (if there is one) for each road segment when a node is in or near an intersection, or selects one relay for forward and backward nodes if it is on a single road. In this way, data can be propagated toward selected directions. (2) If we want to select a relay node on the same road segment as the current node, we select it based on the distance. If we want to select relay nodes on other road segments, we select them based on line-of-sight. Therefore, our protocol prefers nodes in or around an intersection as next relay nodes since they have better line-of-sight.

2.2.4 Data Dissemination Process

To propagate messages on VANETs, we use message labeling techniques similar to [23]. When a node wants to send a message, it attaches the packet ID and the selected relay node IDs to the message. When a node receives a message, it first checks if it has received it before. If yes, it means there is a loop, and the message will be dropped. Otherwise it accepts the message and checks if it is in the selected relay node list. If yes, it replaces the selected relay node list with its own ones and rebroadcasts it.

We explain our data dissemination process with two scenarios in the remainder of this section. The first one is a highway scenario and the second one is an intersection scenario.

- *Scenario 1: Data dissemination on highways*

This example shows how messages are propagated by using two-way traffic flows on a single road, as illustrated in Figure 2-6.

1. Node S wants to send a message. Node A is selected as the forward relay node because it is the farthest node. Node S broadcasts the message.
2. Node A and X receive the message. Both X and A accept this message, but only A rebroadcasts this message.
3. For node A, node B and S are selected as the relay nodes. After they receive the message broadcast by A, node S will not rebroadcast it because it is the sender. Node B will rebroadcast the message.
4. For node B, node A and C are both selected as the relay nodes. Node A will not rebroadcast the message sent by B because it has received the message. Node C will rebroadcast the message.

- *Scenarios 2: Data dissemination at intersections*

In Figure 2-5, node A, D, F and H are selected as the relay nodes. After receiving the message from node S, A, D, G and H will rebroadcast it.

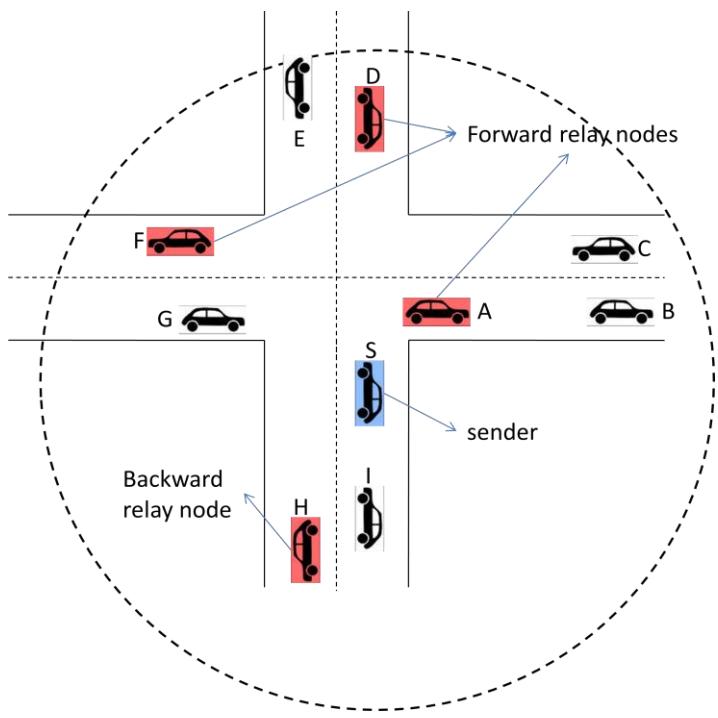


FIGURE 2-5 Relay node selection at the intersection

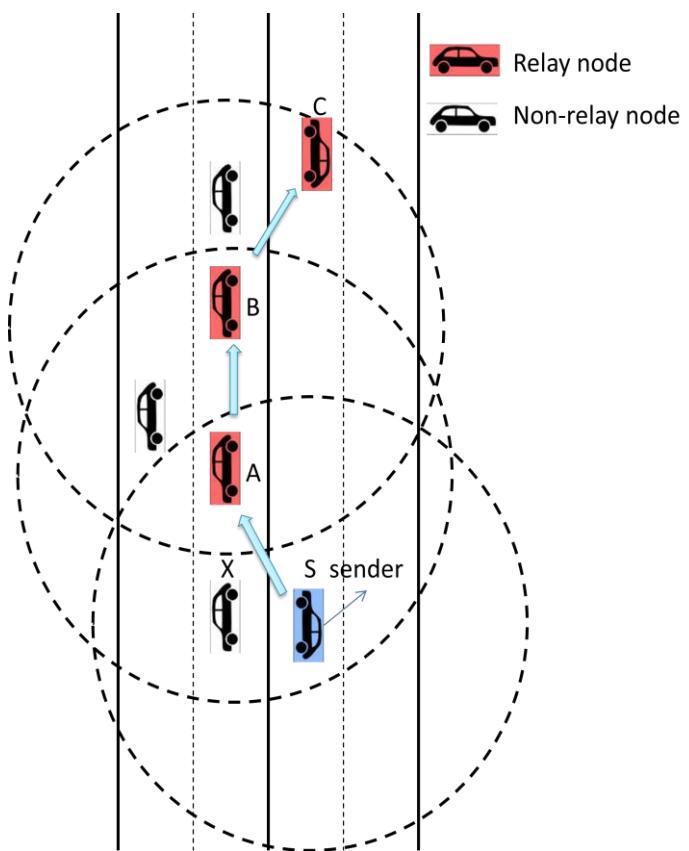


FIGURE 2-6 Data dissemination on highway

2.3 Performance Evaluation

In this section, we evaluate the performance of our protocol. We compare it to several protocols, including Flood, 3-CLASS, and 6-CLASS. 3-CLASS selects one relay for nodes ahead and one for nodes behind, and uses all other nodes as relay nodes. 6-CLASS categorizes vehicles into six groups: ahead, behind, right-ahead, left-ahead, right-behind, left-behind, and selects one relay for each group.

2.3.1 Simulation Model

We choose VanetMobiSim [7] as our traffic generator. It supports IDM_IM (Intelligent Driver Model with Intersection Management) and IDM_LC (Intelligent Driver Model with Lane changes) which consider both macro and micro mobility models. IDM_IM defines two intersection scenarios: crossroads regulated by stop signs and road junctions ruled by traffic signs. IDM_LC considers the situations that vehicles can change lanes or overtake each other. In our simulations, all intersections are ruled by traffic signs. A node arriving at an intersection is randomly to go to any other road segments. Vehicles on roads can overtake each other or change lanes.

The simulations have been done with ns-2.34. We used IEEE 802.11 as the underlying protocol with parameters listed in Table 2-2. We conduct our simulations with different number of node. Each experiment is conducted 50 times and the average values are calculated. To avoid overloading the channel with too many beacons, some techniques can be used to adjust BUP based on vehicle speed, from 0.5s when the speed is over 64 km/h to 10s when the speed is below 8 km/h [8]. Considering the speed settings in our simulation and keeping the accuracy of beacon message, we set BUP to 1s.

TABLE 2-2 SIMULATION PARAMETERS

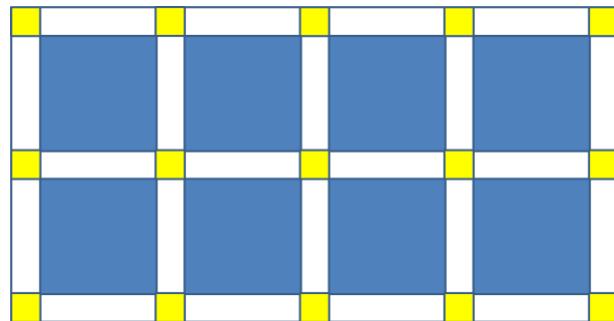
Parameters	Value
Simulated area	1200m X 600m for grid and fork road topology, 600m X 600m for curve road topology
Simulated scenarios	Two-way and two lanes
Transmission range	150m
Road width	20m
Speed ranges	40 ~80 km/h
Number of vehicle	25, 30, 35, 40, 45, 50, 55, 60, 65, 70
Data rate	10Kbps
Packet size	1000 Bytes

We create three different road topologies (Figure 2-7) to test the performance of our protocol. The first one is grid road topology. The blue areas represent obstacles such as buildings, and the yellow areas represent intersections. The second one is a curve road. To simulate a curve road topology, we divide a curve into α straight line segments of equal length. Each line segment represents a short straight road, and all of them form a curve road. The larger α is, the more realistic the curve topology. In this way, it reflects different relative positions and moving directions of vehicle in a curve road. In our simulations, we set α to 10. The third one is a grid road topology with fork intersections. The goal of creating these road topologies is to simulate the diverse road structures in urban environment.

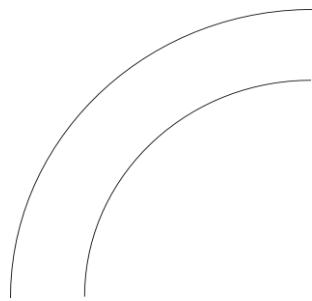
Considering obstacles in urban area, we implement a simple line-of-sight propagation model [11]. Given an intersection, the sight window of a vehicle is defined as the view the vehicle can see limited by the corner of that intersection (Figure 2-8). Two nodes can only communicate to each other if they are in each other's transmission range, and either one of them is in the sight window of the other.

The following metrics are used for performance comparisons:

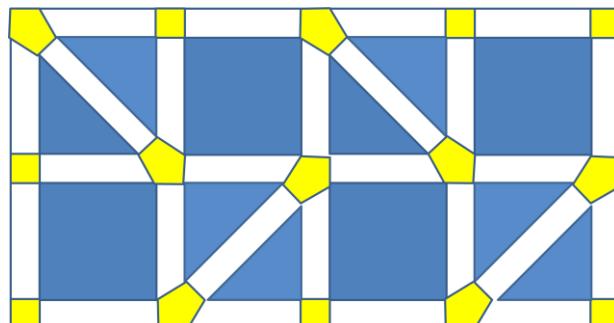
- Average packet efficient percentage: the number of accepted messages over the number of received messages propagated in the scenario.
- Reachability: the average of the number of vehicles that accept a message over the number of vehicles that exist in the simulation when a message is propagated. We use reachability as the metric of reliability. Higher reachability means a protocol selects relay nodes reliably and has higher tolerance to various road topologies.
- Average number of relay per transmission: the number of selected relay when a packet is transmitted. This is an average value per transmission. For Flood, we measure the number of neighbor when a packet is transmitted since Flood uses all neighbors to forward data.
- Beacon overhead: to understand the overhead of our protocol, we measure the average amount of beacon in bits that a node received throughout the simulation.
- Packet overhead: the average size in bits of relay list in a data packet.



(a) Grid road topology



(b) curve road



(c) fork road topology

FIGURE 2-7 The road topologies

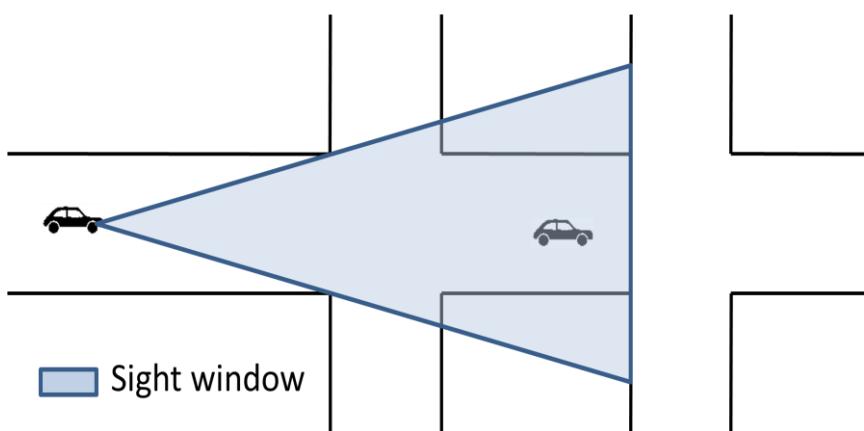


FIGURE 2-8 Sight window.

2.3.2 Simulation Results

Figure 2-9 shows the average packet efficient percentages of three road topologies. Flood suffers from poor packet efficiency as it selects all nodes to rebroadcast messages. 3-CLASS and 6-CLASS are slightly better because they improve packet efficiency by limiting broadcasting in selected directions, but still suffer misclassification problem and thus are not efficient. Our protocol performs much better in packet efficiency in all road topologies. This is because our protocol select only one relay node in each direction and avoid misclassification problem.

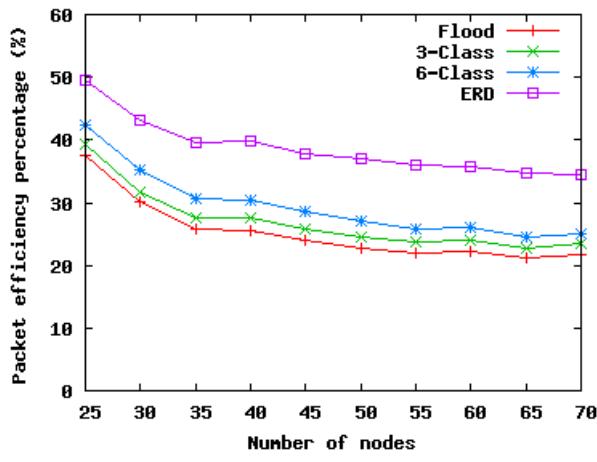
Figure 2-10 shows the simulation results of reachability. On the contrary to intuition, the reachability of all protocols does not increase with the number of node. After investigating the packet trace, we found that as the number of node goes higher, the collision rate goes higher which counteracts the effect of increasing node number. Due to the efficiency, our protocol starts to outperform other protocols when there are 70 nodes in the network for grid and fork topologies, and always achieve better reachability in curve topology.

To evaluate the performance more accurately, we also measured the average number of selected relay per transmission in each topology. Ideally, two relays for forward/backward directions and several more at intersections are required. The more the selected relays, the more the redundant retransmissions a protocol has. Figure 2-11 shows the average number of relay in all road topologies. It is interesting that sometimes 3-CLASS and 6-CLASS use more relays than Flood in a transmission. Obviously, Flood uses more total transmissions in a simulation since it uses all neighbors to forward data, but some nodes may have fewer neighbors which decreases the average selected relays. As we expect, our protocol uses fewest relays to forward data. Less than 3 relays in average are selected in all situations.

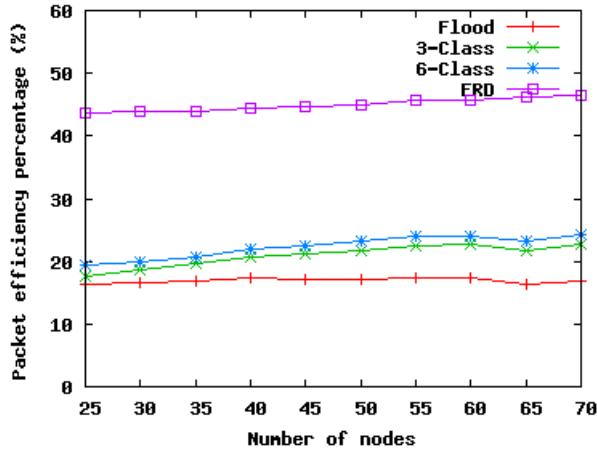
Combined Figure 2-9(b) and Figure 2-11(b), the effect of misclassification is more notable in curve road. While other protocols classify vehicles in different roads and thus select more redundant relays, our protocol classifies them correctly and uses no more than 3 relays. Meanwhile, due to the efficient bandwidth utilization, our protocol avoids collisions during data propagation, and achieves about 80% reachability while that of other protocols drops significantly when there are more nodes in the network (Figure 2-10(b)).

Figure 2-12 shows the beacon overhead. Since Flood does not need to transmit beacons, we did not evaluate beacon overhead for Flood. 3-CLASS and 6-CLASS include node ID and position in beacons, so the beacon size is 160 (32+128) bits. Our protocol exchanges information of node ID, position, road ID, and IsIntersection in beacons, so the beacon size is 193 (32+128+32+1) bits. Intuitively, it will result in 20% more beacon overhead of our protocol compared to others. As we can see in Figure 2-12, the ratio of beacon overhead between our protocol and others is about 120%, which is consistent to our prediction. Since the results are similar in all road topologies, we only show the result of grid topology here.

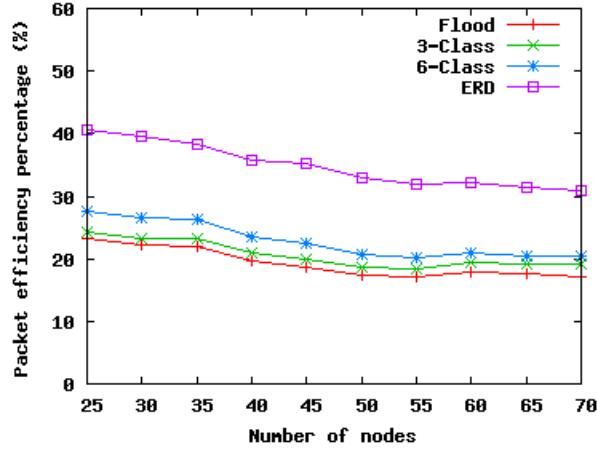
Figure 2-13 shows the packet overhead. The more the selected relays, the higher the packet overhead because the size of the relay list in a data packet is larger. Our protocol has the least packet overhead since it selects less relays. This result is also consistent to the result of the selected relay number, since the size of relay list is in proportion to the selected relay number.



(a) Grid topology

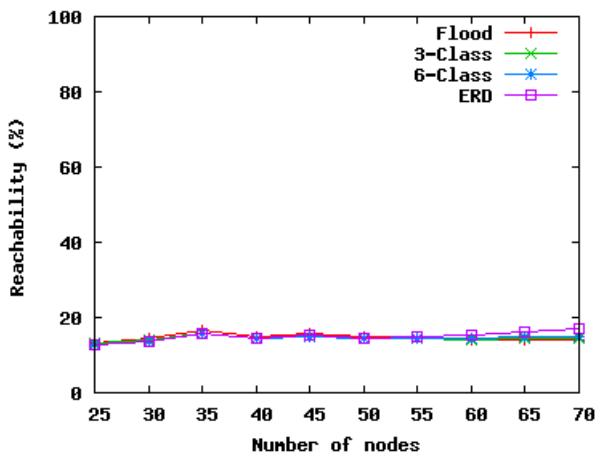


(b) Curve topology

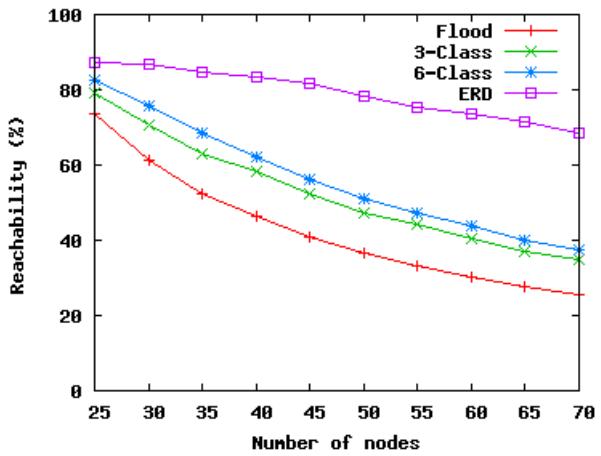


(c) Fork topology

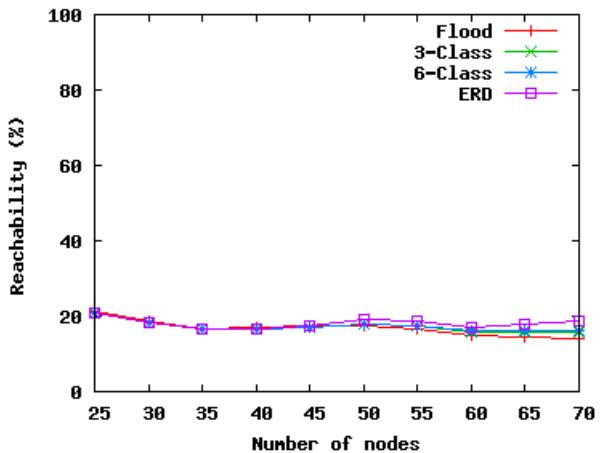
FIGURE 2-9 Average packet efficiency in all road topologies.



(a) Grid topology

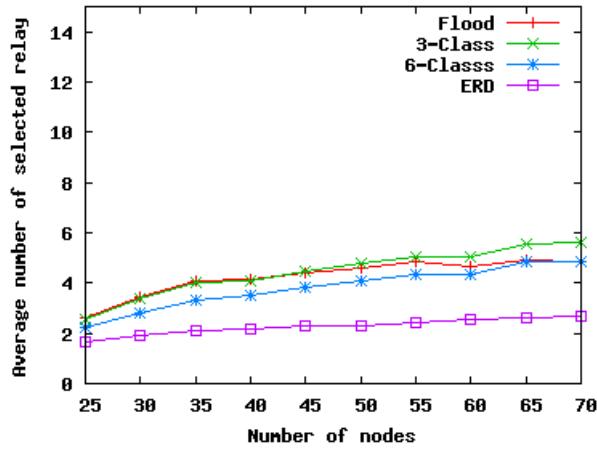


(b) Curve topology

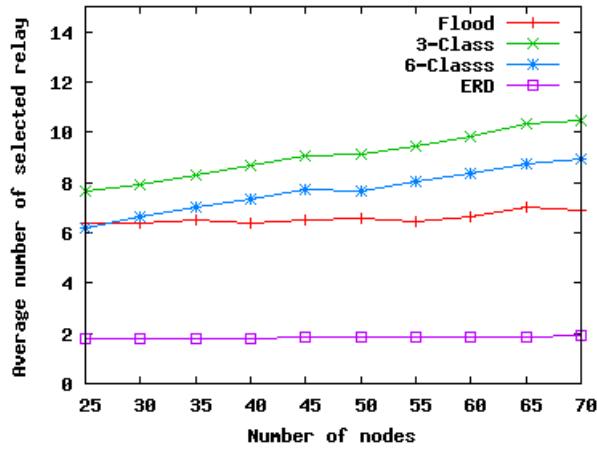


(c) Fork topology

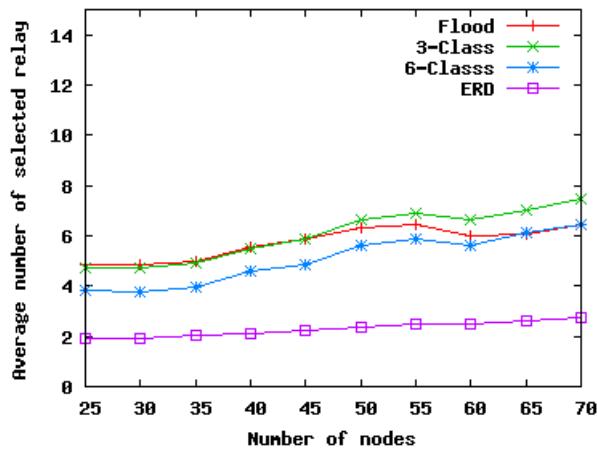
FIGURE 2-10 Reachability in all road topologies



(a) Grid topology



(b) Curve topology



(c) Fork topology

FIGURE 2-11 Average number of selected relay per transmission in all road topologies

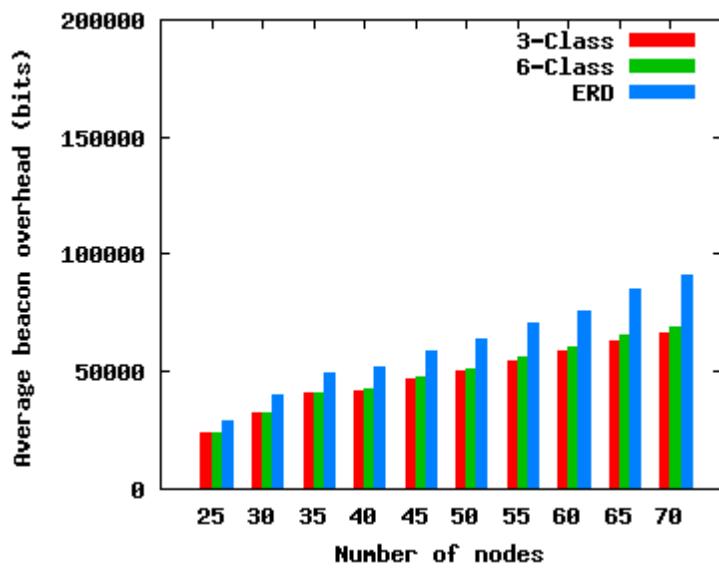
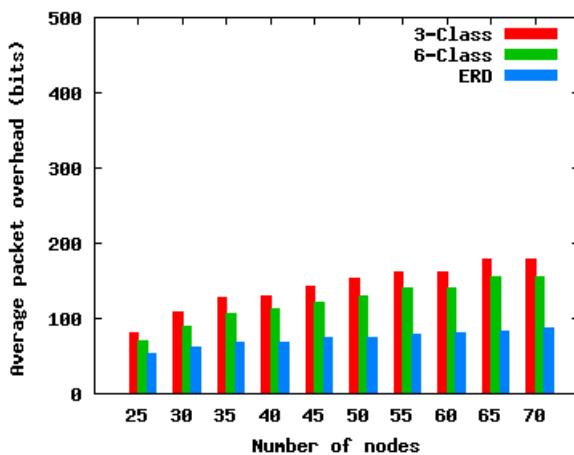
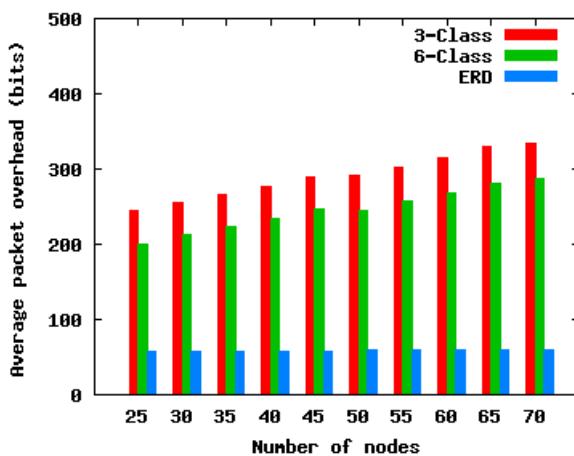


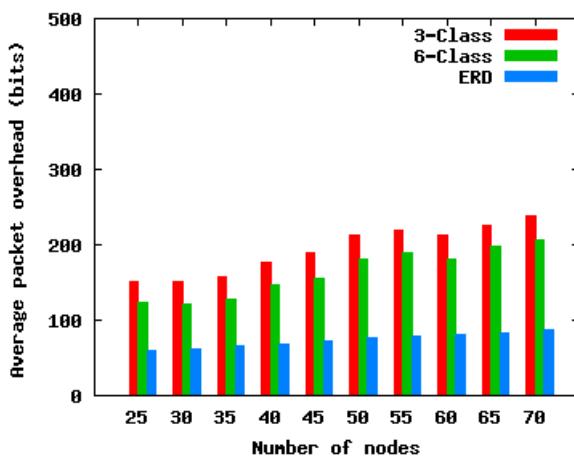
FIGURE 2-12 Beacon overhead (grid topology)



(a) Grid topology



(b) Curve topology



(c) Fork topology

FIGURE 2-13 Packet overhead in all road topologies

2.4 Discussions

Our protocol requires two more information in beacon messages than traditional protocols: a road ID and a field indicating if the current node is in an intersection. This results in more beacon overhead. In fact, we can eliminate this overhead by not including them in beacon messages, but acquiring them when receiving beacons. Since the position information is included in beacon messages, a vehicle can make a query to the navigation system and obtains road ID as well as intersection information for relay selection. In this way, our protocol only exchanges position information in beacons as the traditional protocols do, but improves packet efficiency significantly and reduces the packet overhead.

2.5 Conclusions

The protocol we propose is a novel efficient directional broadcast protocol. With the support of GPS navigation system, our protocol groups vehicles based on road segments, and carefully selects relay node for each group. In this way, our protocol is able to propagate data to vehicles in the selected directions in diverse road topologies. In the simulations, our protocol achieves significant packet efficiency improvement and maintains the same level of reachability as other protocols in all node density and road topologies. Due to its efficiency, our protocol shows the potential of being a promising directional broadcast protocol for VANETs.

Chapter 3 VANET Data Dissemination Using Delay Tolerant Network Forwarding

3.1 Introduction

In this chapter, we incorporate a retransmission mechanism if transmission is regarded as failed to overcome the unreliable wireless communication. Moreover, we use the store-carry-forward approach to increase the delivery ratio and efficiency. The goal is to disseminate messages as extensively as we can, but due to long propagation delay using Delay Tolerant Network (DTN) approach, the messages delivered in this way should not be latency-sensitive such as collision avoidance messages. The example messages include traffic and travel condition data and other non-safety application message data. Simulations show that the retransmission combined with store-carry-forward approach increases delivery ratio significantly. We also analyzed the effect of GPS error on our proposed protocol.

3.1.1 Delay Tolerant Network Forwarding

This section presents a couple of DTN routing approaches proposed for VANEs. Readers can refer to [67] for an overview of the state of the art DTN routing protocols for different types of delay tolerant networks.

Mobile Relay Protocol (MRP) [68] is a relay- based approach that is used in conjunction with traditional ad hoc routing protocol. A node would engage in traditional routing until a route to the destination is unobtainable. It then performs controlled local broadcast to its immediate neighbors. All nodes that receive the broadcast store the packet and enter into the relaying mode.

Such nodes carry the packet until their buffer is full. When that happens, the relay-nodes would choose to relay the packet to a single random neighbor.

Context Aware Routing (CAR) CAR [69] integrates synchronous and asynchronous mechanisms for message delivery. A synchronous message delivery mechanism is characterized by a contemporaneous path between the current node and the destination; whereas, an asynchronous message delivery mechanism does not have such a path. However, CAR did consider weights of each contextual parameter (e.g., rate change of connectivity, battery life, etc.) dynamically. Since CAR uses DSDV for traditional ad hoc routing, it introduces prediction to reduce the overhead of dissemination of routing table. CAR provides another framework of utilizing the contextual information with dynamic-weight consideration geared towards sensor networks and prediction geared towards proactive routing.

Model Based Routing (MBR) Chen et al. [70] presents a model based routing that takes advantage of the predictable node moments along a highway. Authors have verified the hypothesis that the motion of vehicles on a highway can contribute to successful message delivery, provided that messages can be relayed and stored temporarily at moving nodes while waiting for opportunities to be forwarded further.

GeOpps [71] is a delay tolerant routing algorithm that exploits the availability of information from the navigation system (NS). A navigation system includes a GPS device, maps, and the function to calculate a suggested route from current position to a requested destination. GeOpps have vehicles communicate with neighbor's navigation system and use the obtained information to perform efficient and accurate delay tolerant network. A NS is assumed to have the ability to calculate the route to a given destination and to estimate the required time to a given destination. When a vehicle wants to deliver a data packet, it broadcasts the destination of it. The one-hop neighbors of the packet holder will calculate the "Nearest Point" (NP). Since

every vehicle using NS has a suggested path, the NP is the location that is the location on the path which is geographically closest to the destination.

3.2 Proposed Protocol

Our protocol contains three parts: the modifications to GPS navigation system, the relay selection algorithm, and the data dissemination process. The modification to GPS navigation system and the relay selection algorithm has been discussed in the previous chapters. Therefore, in this section, we only elaborate the data dissemination process. We listed the complete relay node selection algorithm here for completeness.

3.2.1 Notations

The followings are the notations that will be used in this chapter:

- *Forward nodes* (\mathbb{F}): nodes ahead of the current vehicle.
- *Backward nodes* (\mathbb{B}): nodes behind the current vehicle.
- *Forward relay node*: the node which is ahead of the current node and is selected as the relay node
- *Backward relay node*: the node which is behind the current node and is selected as the relay node

TABLE 3-1 RELAY SLECTION ALGORITHM

Algorithm 1: relaySelection()

```

1:   if (IsIntersection) then
2:      $\mathbb{S} \leftarrow$  Group nodes based on Road ID i
3:     foreach subset  $\mathbb{S}_i$  in  $\mathbb{S}$ 
4:       do singleRoadRelaySelection( $\mathbb{S}_i$ )
5:   else
6:      $\mathbb{F} \leftarrow$  find all forward nodes
7:     selectFBRelay( $\mathbb{F}$ )

```

TABLE 3-2 FB RELAY SELECTION ALGORITHM

Algorithm 2: selectFBRelay(\mathbb{N})

```

1:   if (the current node is near an intersection) then
2:     if (a node  $\mathcal{N} \in \mathbb{N}$  is an intersection) then
3:       select  $\mathcal{N}$ 
4:     else
5:        $\mathbb{S} \leftarrow$  Group nodes based on Road ID i
6:       foreach subset  $\mathbb{S}_i$  in  $\mathbb{S}$ 
7:         do LOSRelaySelection( $\mathbb{S}_i$ )
8:     endif
9:   else

```

TABLE 3-3 LOS RELAY SELECTION ALGORITHM

Algorithm 3: LOSRelaySelection (\mathbb{N})

1. **foreach** $\mathcal{N} \in \mathbb{N}$
 2. **do** Calculate the angle between the moving direction of the current node and the relative position from the current node to \mathcal{N}
 - 3.
4. **if** (a node $\mathcal{N} \in \mathbb{N}$ is a forward node)
 5. Select the node $\mathcal{N} \in \mathbb{N}$ with $\min(\text{angle})$
6. **else**

3.2.2 Data Dissemination Process

To propagate data in VANETs, the sender attaches the selected relay node IDs to the message when it has data to broadcast. When a node receives a message, it first checks if it has received it before. If yes, it means there is a loop, and the message will be dropped. Otherwise it accepts the message and checks if it is in the selected relay node list. If yes, it replaces the selected relay node list with its own ones and rebroadcasts it.

The wireless link in urban area is not reliable. Our protocol addresses this problem as follows. When a node (re)broadcasts a packet, it sets up a timer and listens for a duplicate packet transmitted by the relay nodes. The duplicate packet functions as an implicit ACK. If a duplicate packet is overheard before the timer expires, the sender cancels the timer and stop retransmission. Otherwise it retransmits the packet after timer expires and listens for a duplicate packet again. The retransmission process repeats until a duplicate packet is heard, or the maximum retransmission time is reached.

Due to the rapidly-changed network topology in VANETs, it is possible that the network is disconnected when a node wants to send data. In this case, the node is isolated. We say it is in the **DTN mode**. To deal with this problem, we use the store-carry-forward approach. When a node wants to send data but there is no neighbor in the neighbor list, it stores the packet in the buffer, until a beacon message is received from a new neighbor. After that, these two nodes exchange the packets they stored in DTN buffer. Only the packets that are not in DTN buffer will be broadcast. Another situation that a node will buffer a packet is when the maximum retransmission time is reached. In this case, the data retransmission is regarded as failed, and the packet will be buffered until a new neighbor is found. The packet will be rebroadcast again then.

Combined with retransmission mechanism and DTN forwarding, data should be propagated until they are diffused to the whole network. This consumes excessive bandwidth and is usually not the desirable result. For example, information about a traffic jam is usually interested by drivers around the incident scene rather than drivers in another city. In our protocol, we suggest to use two metrics to limit the broadcast effect: zone of interest (ZOI) and timespan. ZOI is defined as the geographical boundary in which the data should be propagated. If the data is received outside its ZOI, it will be discarded. The timespan defines the span of time which the data should be propagated. This metric can be used to purge outdated data. Both metrics can be attached to a data packet during propagation so that receivers can handle the packet accordingly.

3.3 Performance Evaluation

In this section, we evaluated the performance of our protocol. We implemented FLOOD, 6-CLASS, Map-based (RB), and RB+retx+DTN. FLOOD uses a simple flooding technique to disseminate packets, i.e., all neighbors are used to forward packets. 6-CLASS protocol is a directional broadcast protocol which divides neighbor nodes into 6 groups based on the relative position, and selects one relay node in each group. RB is a map-based protocol which uses road topology to classify neighbors. The last protocol uses data retransmission and DTN forwarding in addition to map-based broadcast, as we mentioned earlier. In this way, we know how our solutions can impact the performance.

3.3.1 Simulation Model

The traffic generator in this simulation is VanetMobiSim [7]. The mobility model used in our simulations is described as follows: if a vehicle approaches another one ahead, it slows

down. If no vehicle is ahead, it can speed up until it reaches the speed limit. Vehicles on roads can overtake each other or change lanes. All intersections are ruled by traffic signs. A node arriving at an intersection is randomly to go to any other road segments.

We create three different road topologies to test the performance of our protocol. The first one is a highway. There is no obstacle in this topology. The second one is a grid road topology. The blue areas represent obstacles such as buildings, and the yellow areas represent intersections. The third one is a fork road topology. The goal of creating these road topologies is to simulate the diverse road structures in urban environment.

It is difficult to provide a realistic radio propagation model for urban environment because of the complex interference between the signal and its reflections caused by buildings. Considering obstacles in urban area, we implement a simple line-of-sight radio propagation model [10][12]. Given an intersection, the sight window of a vehicle is defined as the view the vehicle can see limited by the corner of that intersection. Two nodes can only communicate to each other if they are in the transmission range, and either one of them is in the sight window of the other. If two nodes are in line-of-sight, data are propagated according to two-ray ground propagation model. Combined with line-of-sight and two-ray ground relay propagation model, we think it offers a good balance between the computational cost and accuracy.

The simulations have been done with ns-2.34. We used IEEE 802.11p as the underlying protocol with parameters listed in Table 3-4. We conducted our simulations with different number of nodes. Each simulation has 10 runs and the average values are calculated. In each run, all nodes start sending packets at the 21th second plus a small random shift period to skip the initial node movement. The small random shift time period is used to avoid collision for the first data transmission. All nodes stop generating packets at the 80th second but keep forwarding until simulation ends so that we can observe the forwarding process of RB+retx+DTN. In our simulations, we assume there is no limit of buffer size, i.e., each node

is capable of buffering all packets in DTN mode. Also, the zone of interest of each packet is the whole simulation area and the timespan is the simulation time. Therefore, a packet in DTN mode should be disseminated in the network until all nodes receive it or the simulation ends.

The following metrics are used for performance comparisons:

- Packet efficient percentage: the number of accepted messages over the number of received messages propagated in the scenario.
- Reachability: the average of the number of vehicles that accept a message over the number of vehicles that exist in the simulation when a message is propagated. We use reachability as the metric of reliability. Higher reachability means a protocol selects relay nodes reliably and has higher tolerance to various road topologies.
- Number of relays per transmission: the number of selected relay when a packet is transmitted. This is an average value per transmission. For Flood, we measure the number of neighbor when a packet is transmitted since Flood uses all neighbors to forward data.
- Propagation delay: the period between the time a packet has been transmitted for the first time to the time the packet has been received for the last time.

TABLE 3-4 SIMULATION PARAMETERS

Parameters	Value
Simulated area	1200m X 600m for grid and fork road topologies, 600m X 1000m for highway
Simulated scenarios	Two-way and two lanes for grid and fork road topology, two-way and four lanes for highway
Propagation model	Two-ray ground combined with line-of-sight propagation model
Transmission range	300m
Road width	30m
Speed ranges	20~60 km/h for grid and fork topology, 60~120 km/h for freeway
Data rate	10Kbps

3.3.2 Simulation Results

Figure 3-1 shows the packet efficient percentages of three road topologies. FLOOD suffers from poor packet efficiency as it selects all nodes to rebroadcast packets. 6-CLASS is better because it improves packet efficiency by limiting broadcasting in the selected directions, but it can select up to 6 relays and thus are not efficient. RB uses road information to avoid selecting redundant relay nodes, so it achieves the best efficiency. For RB+retx+DTN, the packet efficiency is comparable to FLOOD. This is because packets are retransmitted if transmissions failed or network is disconnected.

Figure 3-2 shows the simulation results of reachability. Figure 3-4 shows the number of collisions throughout simulations. In highway topology, the reachability of FLOOD increases slightly with node number at beginning, but drops quickly then. This is because packet collision happens frequently when node number grows. In general, RB performs no poorer than FLOOD and 6-CLASS in terms of reachability. We observed the reachability of FLOOD, 6-CLASS and RB is low in grid and fork topologies. There are two reasons for this: 1) the collision happens frequently when node number grows which causes data dissemination stops. 2) nodes tend to accumulate at intersections waiting for traffic lights. It makes the network partially connected even though node number increases. This phenomenon also conforms to the results in [19], which states that the coexistence of the broadcast storm and the disconnected network happens in urban scenarios. DTN forwarding helps bridge gaps between vehicles. Because RB+retx+DTN uses retransmission and DTN forwarding, it keeps the best reachability in all cases.

As we can see in Figure 3-3, using road topology information can keep the number of selected relay nodes per transmission to about 2. This is a very satisfactory result because in ideal situation, we need two relays in a single road (one for forward direction and one for

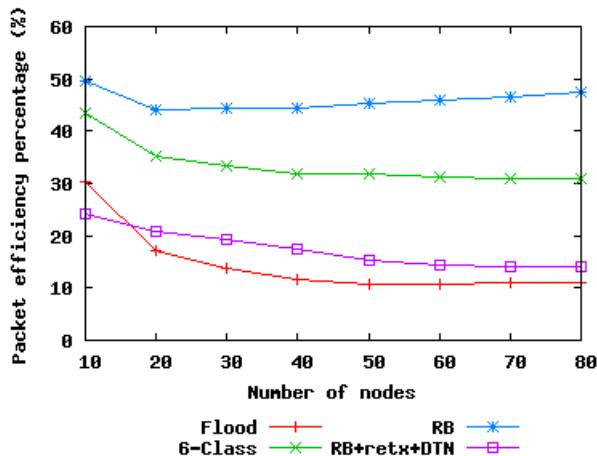
backward direction) and several more in an intersection. FLOOD can use up to 10 relays per transmission when there is large number of nodes in the network.

Figure 3-5 shows the propagation delay for all road topologies. It is reasonable that RB+retx+DTN has delay much larger than other protocols. Usually the delay is lower than 160 seconds which is not a very long period.

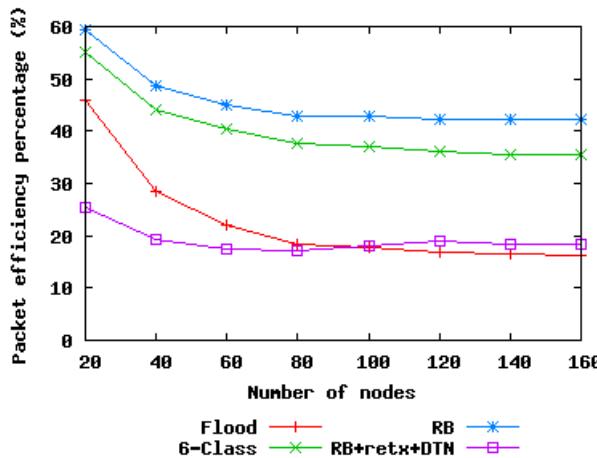
In conclusion, the map-based approach demonstrates its efficiency from the simulations. This also makes it scale well with the node numbers. For network with rapidly changed network topology such as VANET, using DTN forwarding can improve the reachability significantly, with the tradeoff of packet efficiency and propagation delay. Combined with the map-based relay selection, the packet efficiency of DTN fowrading is similar to flooding, and the delay is not very long to achieve high reachability. Therefore, RB+retx+DTN offers a promising data dissemination mechanism for VANETs.

Another factor which may affect the performance is GPS accuracy. The average accuracy of modern commercial GPS is about 15 meters [6]. With this error, a node can be mistakenly selected as a relay which may reduce efficiency and reliability. We also evaluate the performance under GPS error condition. When a node sends a beacon, we add an error ε to the (x, y) coordinates deliberately. As a consequence, coordinate (x, y) becomes $(x \pm \varepsilon, y \pm \varepsilon)$ where $0 \leq \varepsilon \leq 20$ meters. The value of error follows the uniform distribution. Figure 3-6 show the simulation results of reachability. The solid lines represent results without GPS errors and symbols represent results with GPS errors. The results with GPS error and without for all protocols are very similar – just about 1% difference. As we can imagine, the performance of FLOOD are not affected by GPS error since all nodes are used to rebroadcast data. Similarly, 6-CLASS is not affected much because it selects up to 6 neighbors as relay nodes. For map-based approach, GPS error simply causes the relay selection not to select the best relay (the farthest node) and the data propagation is not affected mostly. In fact, the

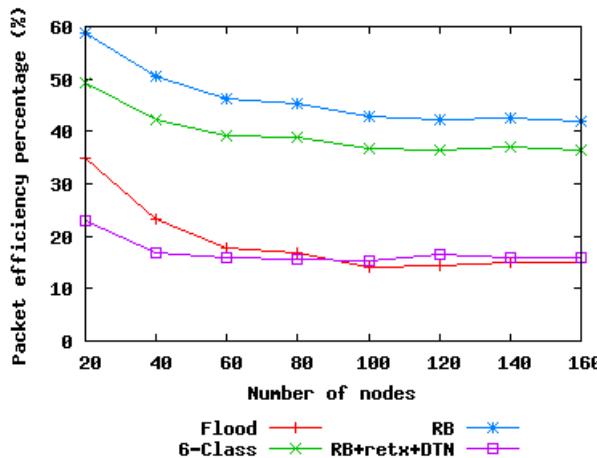
beacons are not updated in real-time, and thus the coordinates in beacons are not precisely the location of vehicle when data packets are transmitted. The simulation shows the map-based approach is resilient against GPS errors even though only two relay nodes on average are used. We show the reachability and skip others since all results are similar.



(a) Highway topology

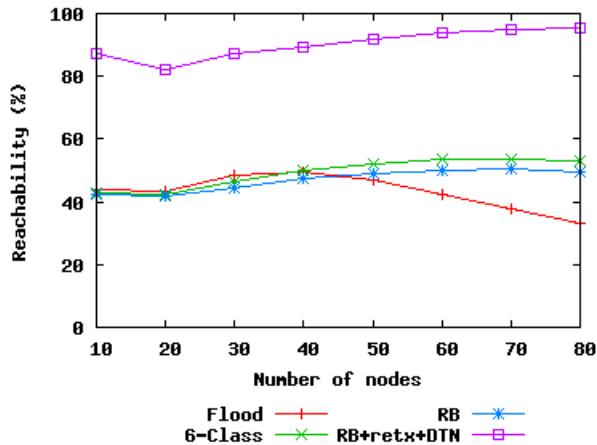


(b) Grid topology

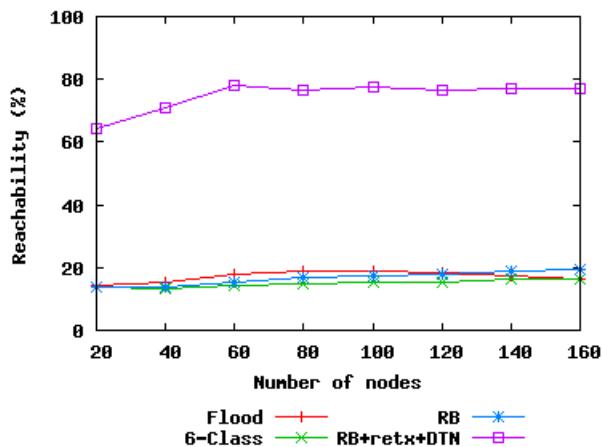


(c) Fork topology

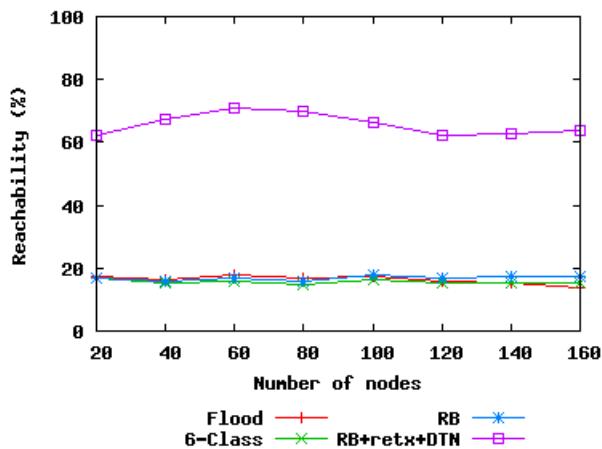
FIGURE 3-1 Packet efficiency



(a) Highway topology

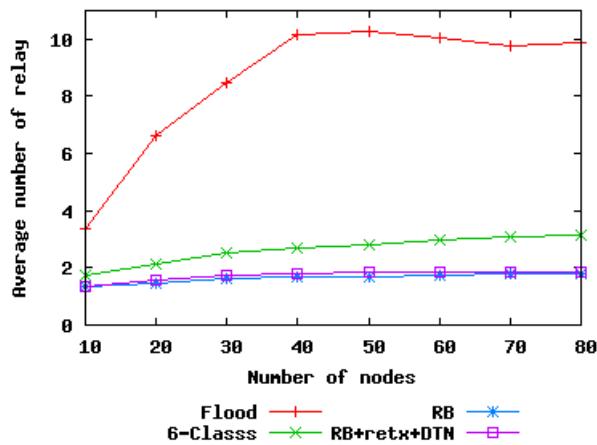


(b) Grid topology

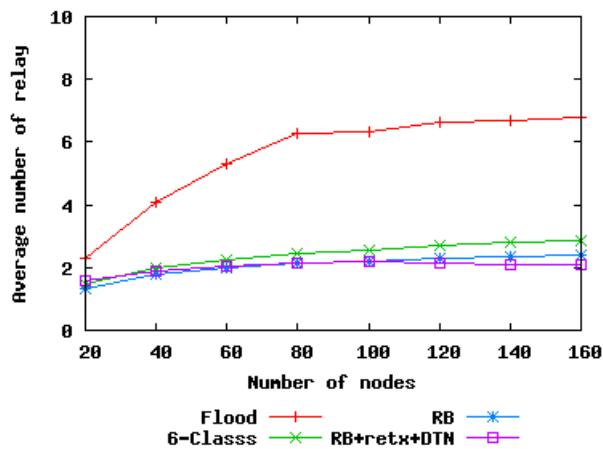


(c) Fork topology

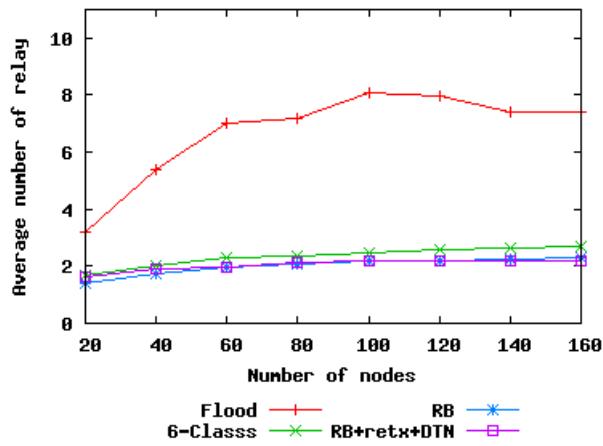
FIGURE 3-2 Reachability



(a) Highway topology

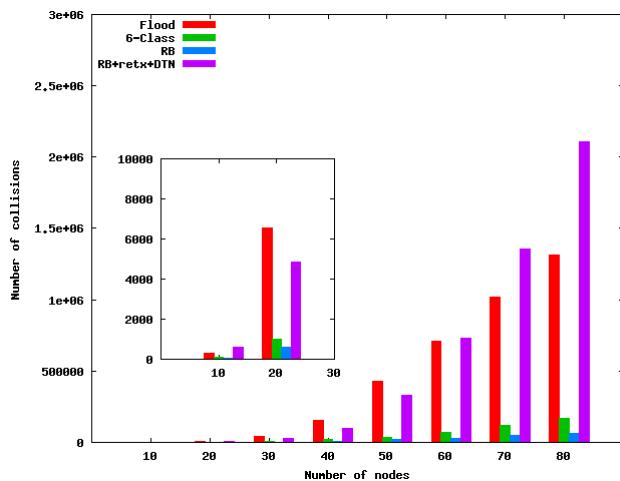


(b) Grid topology

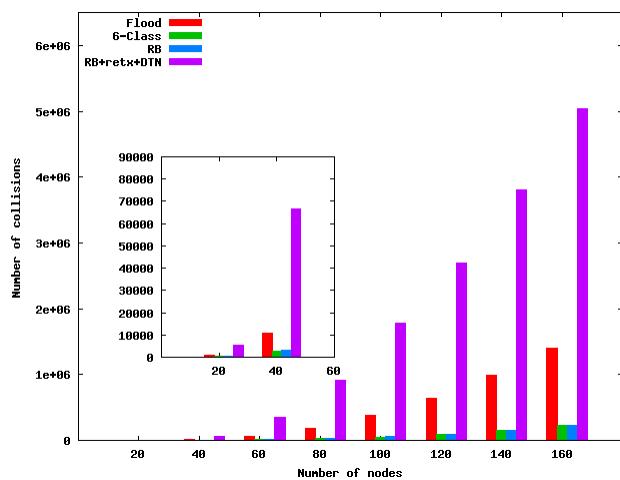


(c) Fork topology

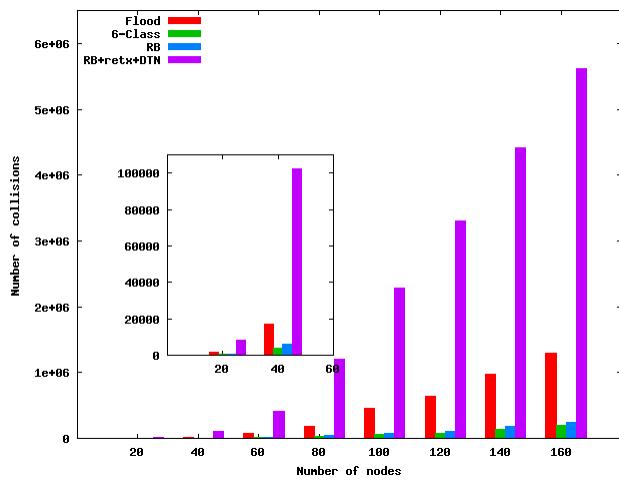
FIGURE 3-3 Number of selected relay per transmission



(a) Highway topology

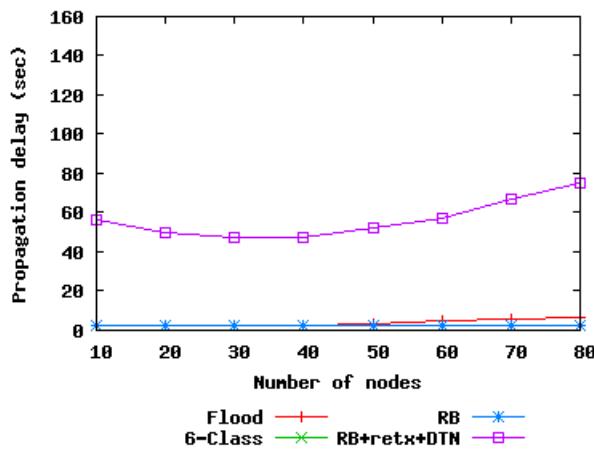


(b) Grid topology

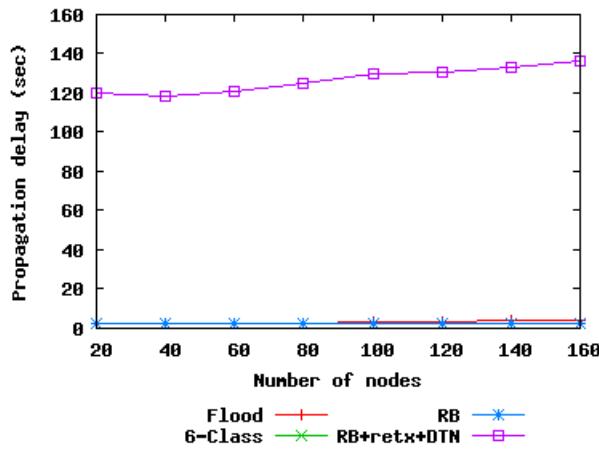


(c) Fork topology

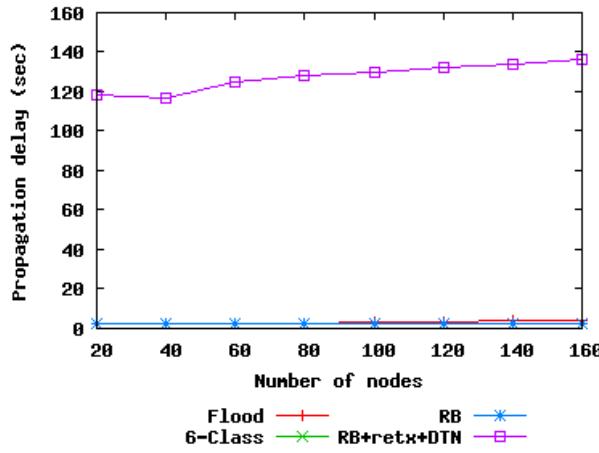
FIGURE 3-4 Number of collisions



(a) Highway topology

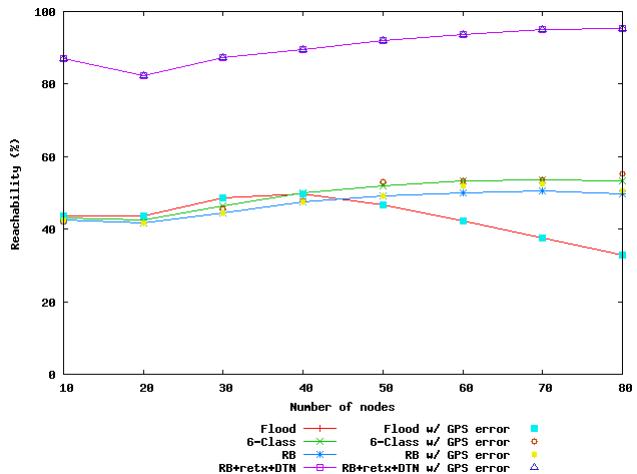


(b) Grid topology

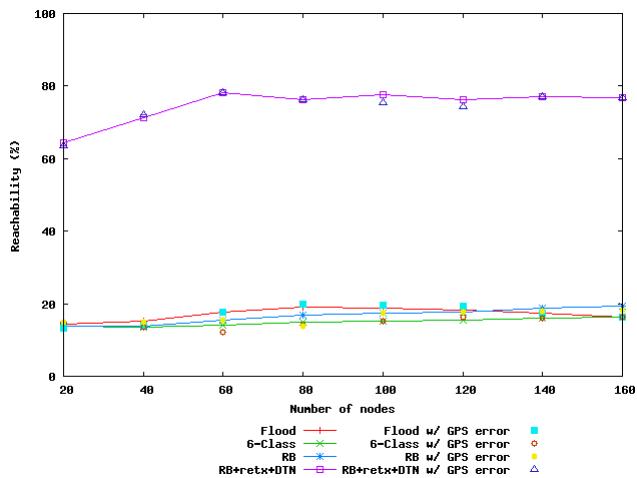


(c) Fork topology

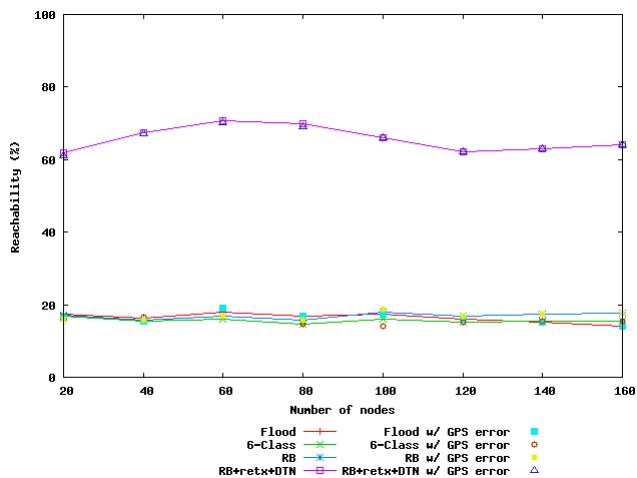
FIGURE 3-5 Propagation delay



(a) Highway topology



(b) Grid topology



(c) Fork topology

FIGURE 3-6 Reachability with gps error

3.4 Conclusions

In this chapter, we addressed two main issues in VANET broadcast: the efficiency and reliability. We proposed a new efficient directional broadcast protocol using road topology information. With the support of GPS navigation system, our protocol group vehicles bases on road segments, and carefully selects relay node for each group. In this way, our protocol is able to propagate data to vehicles in the selected directions in diverse road topologies. In addition, we also applied a data retransmission mechanism and DTN forwarding in our design to improve reachability. In the simulations, the map-based broadcast protocol improves packet efficiency and maintains the same level of reachability as traditional broadcast protocols. Using data retransmission and DTN forwarding improves reachability significantly with the tradeoff of packet efficiency. However, the packet efficiency is still comparable to flooding.

In conclusion, we think using the road topology information is a right direction for future VANET broadcast researches under the premise of the prevalence of GPS. For network with rapidly changed network topology such as VANET, adopting DTN forwarding as a complement of VANET broadcasting is a necessity for achieving high reachability.

Chapter 4 Bicycle-Vehicle Intersection Collision Avoidance Using DSRC and Camera

4.1 Introduction

In modern societies, there is a growing trend of bicycling. People like to ride bicycles because of various reasons – entertainment, personal health, environmental protection, and commute, etc. Governments also encourage people to ride bikes by providing shared bikes in order to reduce pollution and traffic jams. As the popularity of bicycling grows, the need to provide safety to bicyclists increases.

One of the most severe problems of the safety of bicycling is bicycle-vehicle crashes. In United States, there are 677 people died in bicycle-vehicle crashes in 2011 [74]. Among these, 31% people were killed at intersection area. In Japan, more than 1,000 people have died each year in bicycle-vehicle accidents since 1988 [75]. The main reason that the high percentage of bicycle-vehicle crashes happens at intersections is that vehicles can make turns at intersections and bicycles are easily get into the blind spot of vehicles because of small volume. It is imperative to improve the drivers' perception at intersections.

To prevent bicycle-vehicle crashes, some solutions have been proposed. Previous research proposes to detect bicycles with on-board sensing systems using cameras, radar, or LiDAR (Light Detection And Ranging). For camera sensing system, vision recognition algorithm is used to detect pedestrians or bicycles. For example, pedestrians and bicycles can be identified using HOG (Histogram of Oriented Gradient) combined with a linear SVM (Support Vector Machine). These methods help car drivers identify bicycles in blind spots (case 1 in Figure 4-1).

However, using sensors such as cameras, radar, or LiDAR suffers from limited LOS range due to obstacles. For example, a bicycle can be in the Non-Line-of-Sight (NLOS) spot of a car caused by a big trunk in the middle (case 2 in Figure 4-1).

On the other hand, GPS + wireless device has been proposed for vehicle intersection collision avoidance. GPS is used to locate the position of vehicles and wireless devices are used to exchange position information. In [79][80][81], the authors studied a system using inter-vehicle communications that exchanges an absolute position obtained from GPS with each other. While this may work for vehicles, it does not intend to provide safety to bicyclists. First of all, GPS accuracy is generally around 10-15 meters. The accuracy can be improved using sensors (steer sensors, speed sensors, yaw rate sensors, etc.) to improve the accuracy. However, these sensors are unlikely to be installed on bicycles. Without these sensors, the system cannot provide good enough position accuracy for bicycles. Secondly, bicycles may not be able to equip wireless communication technology such as DSRC (Dedicated Short Range Communication) to transmit location information.

Moreover, the perception range of all above mentioned methods (camera, radar, LiDAR and wireless communication) also restricted by the LOS condition provided by intersection structure (case 3 in Figure 4-1). In [34], T. Mangel et al. analyze the LOS condition using real city map and building structure. The results show that only small percentage of intersection can provide good enough LOS. Although the study is conducted targeting intersection collision avoidance for vehicles, the methodology can be applied to bicycle-vehicle collision avoidance as well.

To improve the LOS condition at intersections, sensors can be installed at intersections to detect traffic participants. The sensors can be either cameras or wireless repeaters. In [82], the authors propose to install 10 cameras (8 CCD and 2 HD cameras) at intersections to track moving objects. The position information then will be forwarded to cars approaching

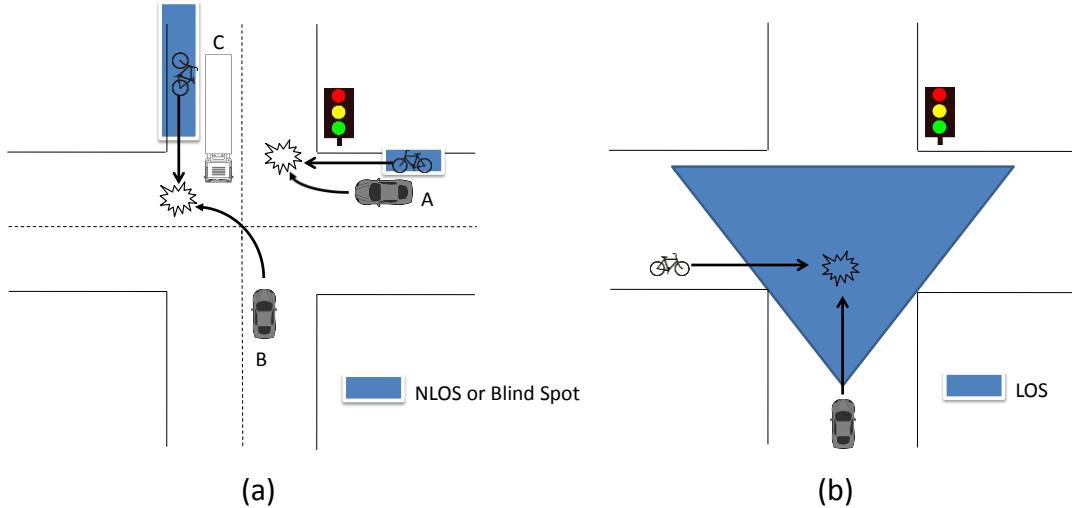


FIGURE 4-1 Bicycle-vehicle collision cases.

- (A) Case 1: car a turns right and collides with a bicycle in the blind spot. Case2: car b turns left and collides with a bicycle in nlos caused by a big trunk.
- (B) Case 3:a car collides with a bicycle because poor los condition. This could happen in a stop sign controlled or uncontrolled intersection or in the transition between green light and red light.

intersections through wireless communication. On the other hand, field tests of collision warning systems at intersections are conducted in California [83] and Minnesota [84] using DSRC. The DSRC connected vehicle project includes the deployment of road-side-units (RSU) at intersections. However, the infrastructure sensors are much more expensive than on-board sensors. Due to the cost, the deployment of RSU has been indefinitely postponed. As a result, a new system targeting bicycle-vehicle collision prevention is needed.

In this chapter, we propose to use both DSRC devices and cameras for bicycle-vehicle collision prevention at intersections. We assume each car is equipped with DSRC devices, so they can exchange information with each other. We also assume each car has a camera installed in the front for bicycle tracking. A vision recognition algorithm is used to identify bicycles from

videos. This may increase the deployment cost, however, installing a camera on vehicle has become a trend as the demand of vehicle accident reconstruction grows. With these assumptions, a vehicle can detect bicycles and disseminate its position information to other vehicles. A map based protocol which selects relay nodes around intersections is used to increase the reachability of data dissemination. Car drivers can be warned as soon as their maneuver causes potential collision. In this way, cars become the “eyes” of other cars at intersections and therefore avoid collisions.

4.2 Related Work

4.2.1 Bicycle Detection

Most research has been done on the topic of pedestrian detection and tracking using vision-based approach. Generally speaking, two approaches are proposed: single template and part-based. In a single template approach, the model captures a whole human body pattern using a single detection window. In [76], the authors propose to use a single camera sensor and histograms of oriented gradients (HOG) algorithm to detect pedestrians. On the other hand, in a part-based approach, it captures the pattern of each part and then combines results to make a final decision for pedestrian detection. Generally, part-based approaches can handle with varying appearances of pedestrians due to clothing, pose, and occlusion, and thus, provide a more complex model for a pedestrian detection problem.

Similar approaches can be used for bicycle detection. The challenge is that a bicycle presents dramatic appearance changes according to camera viewpoints. One of the common solutions to tackle this problem is to establish part-based model for an object of interest. In [85], a mixture model of multiple viewpoints is defined and trained via a Support Vector Machine (SVM) to

detect bicycles under a variety of circumstances. An extended Kalman filter (EKF) is used to estimate the position and velocity of the bicycle in vehicle coordinates. In [86], the leg movement, which can be recognized by using spatiotemporal 3D Gabor filtering, can discriminate bicycles from similar objects such as motorbikes.

Other sensors, such as laser or LiDAR, can also be used to detect and tracking object. In [77], K. C. Fuerstenberg uses laser sensor for detecting obstacles in front of the vehicle, and applied this system to driving safety at intersections. In [78], S. Zeng designs a tracking system using multiple LiDAR sensors. A joint algorithm for estimating motion and a nonparametric contour model is designed. The proposed algorithm can be used to detect objects with any shape (cars, pedestrians, bicycles, etc.).

4.2.2 DSRC at Intersections

One major goal of DSRC is to provide reliable communication between vehicles. The communication of DSRC is usually assumed to be line-of-sight communication. While DSRC may offer partial non-line-of-sight communication, it is not reliable and should not assume to be valid for safety application. This is especially true in urban area in which buildings located around intersections is a common scene. Therefore, the connected vehicle research [87] conducted by U.S. Department of Transportation requires the deployment of RSUs along the road and around intersections. By connecting to infrastructure through RSUs, safety messages can be propagated well around intersections.

The connected vehicle test-bed shows evidence of prove of concept of safety applications using DSRC. There are 10 vehicles equipped with onboard units including DSRC radios for testing purpose. The test-bed includes the deployment of 55 RSUs along interstate highway and arterial roadways within a typical suburban area near Detroit. All RSUs connect to a backend data center offering data such as traffic or weather information. However, due to the cost, the



Figure 4-2 Event data recorder.

country-wide deployment of RSUs has been indefinitely postponed. Without RSUs, beacons do not propagate well at intersections.

4.2.3 Event data recorder

Motor vehicle Event Data Recorder (MVEDR) is an electronic data recording device installed in a vehicle to save images, video, vehicle travel information on a disk during normal driving, pre-crash, in-crash and post-crash stages. It is usually referred to as a “black box” of vehicles.

MVEDR is also part of a car's safety system. The information it records can be used for collision warning system to make real-time decisions, for example, whether to pull seat belts tighter or inflate the airbags.

Installing the MVEDR may increase the cost of car manufacturing. However, there is a trend that more and more new cars have equipped with MVEDR because it is very useful for vehicle crash reconstruction which resolves the disputation between litigants. In this chapter, we assume a vision recognition algorithm is integrated in EDR to detect bicycles. This only requires software update on existing device which minimizes the deployment cost.

4.3 System Overview

4.3.1 Target bicycle-vehicle crash cases

In this chapter, we target three most popular bicycle-vehicle crash cases. The first crash case happens when a car wants to make a right turn, but is not able to sense the existence of the bicycle in the blind spot. The car hits the bicycle while the bicycle keeps going across the intersection. In the second case, a car wants to turn left, but hits a bicycle going forward in the opposite direction. The vision of the car driver is blocked by the trunk in-between the car and the bicycle. The third case happens when a bicycle and a car coming into the intersection from different directions. The car driver is not able to recognize the bicycle because the LOS is blocked by buildings or other obstacles around the corner. This could happen when the bicycle or the car rushes through the intersection during the transition of traffic signal, or at the stop sign controlled or uncontrolled intersections (Figure 4-1).

4.3.2 System architecture

Figure 4-3 shows the system architecture of the bicycle-vehicle collision prevention system. There are several components in the system: the core, the image processing unit, the wireless communication unit, and the in-vehicle sensors. The core has the computational power for analyzing input data and determining a potential collision. The image processing unit runs the vision recognition algorithm to detect a bicycle and extract its relative position. The camera installed in the windshield of a car inputs video to image processing unit. More advanced system can have multiple cameras installed in different position to cover bigger range. The in-vehicle sensors include GPS receiver, accelerometer, gyroscope, and steer sensor. The main purpose of the in-vehicle sensors is to provide accurate GPS position of a car [88]. The sensors

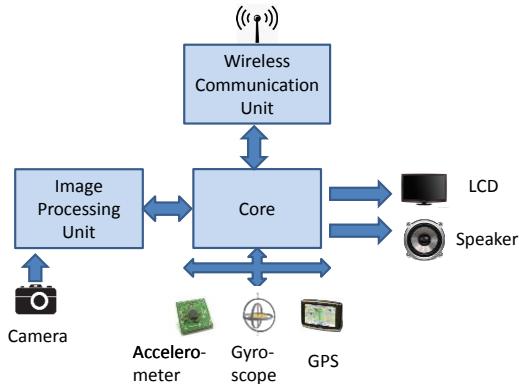
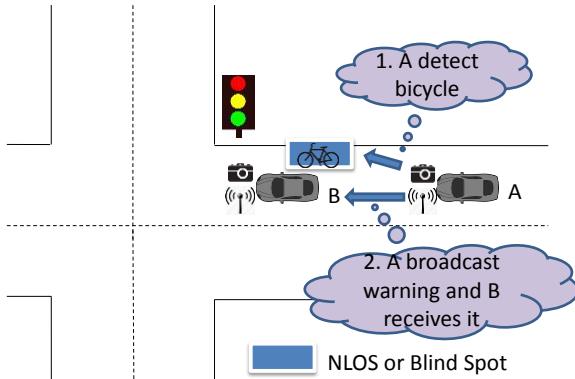


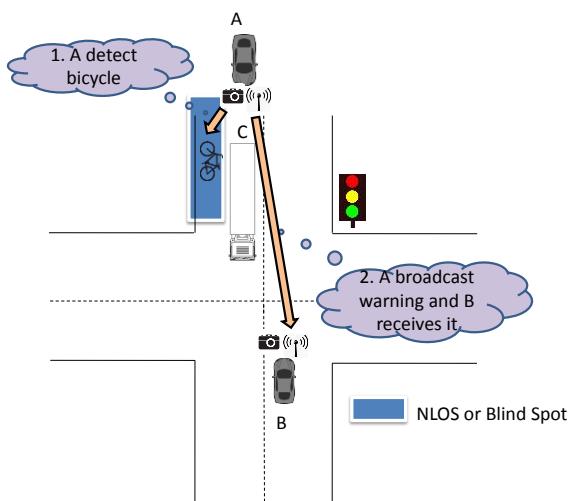
FIGURE 4-3 Bicycle-vehicle collision avoidance system block diagram.

connect the core through controller area network (CAN) [91]. The controller area network is a vehicle bus standard designed to allow devices to communicate with each other within a vehicle with a CAN controller. The wireless communication unit provides the ability to exchange data with neighboring vehicles. Based on the analysis of data from image processing unit, wireless communication unit, and sensors, the core determines if there is a potential collision. If so, a warning will be issued to drivers either by sound or by video or by both.

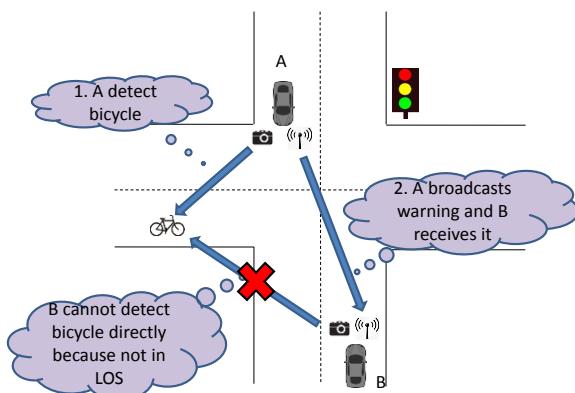
The implementation can be realized by a network distributed embedded system. For example, the DMATEK DMA-NAV270 Development Platform [89] can be used as the core chip. It offers abundant application interface including audio, video, network, and GPS interfaces. The Texas Instrument DaVinci DM6446 Digital Video Evaluation Module [90] can be used as the image processing unit. DSRC is used as the wireless communication technology. The MAC (Media Access Control) layer protocol of DSRC is 802.11p. The deviations of 802.11p from the 802.11 standard are minimized so that the cost of supporting 802.11p for current 802.11 vendors can be reduced. Although there are not many DSRC devices in the market, it is not unrealistic that in the future most 802.11 chip will support 802.11p.



(a)



(b)



(c)

FIGURE 4-4 Using cameras and DSRC for bicycle-vehicle collision prevention. Cars cooperatively detect bicycles and exchange bicycle position to prevent collision. With these “eyes”, the driver perception increases drastically.

4.4 Bicycle-Vehicle Collision Prevention at Intersections

Our idea is to utilize cars around an intersection to collaboratively identify bicycles and transmit their position information. To utilize cars around an intersection for forwarding bicycle warning message, each car exchanges beacon messages containing the position of bicycles periodically. The beacon message generally contains the status of the car, including speed, position, acceleration, etc. With the knowledge of the position of neighboring cars, our map based protocol selects one relay car in each road segment attached to the intersection. This can be done using the map in GPS navigation system. Given the GPS coordinates, the GPS navigation system returns the road ID on which the car is running. The cars closest to the center of the intersection will be selected as the relay nodes. For example, in Figure 4-5, there are four road segments attached to the intersection. For the sender S, car A, B and C are selected as the relay nodes.

When a bicycle is detected, the position of a bicycle is extracted using the image processing

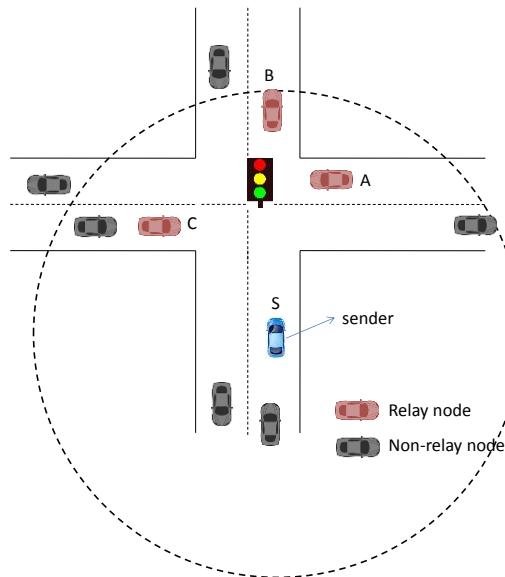


FIGURE 4-5 Select the car closest to the intersection as the relay node for each road segment.

unit in our system. The details of bicycle detection can be found in [76][77][78][85][86]. The bicycle position is a relative position to the car, so it will be converted to an absolute position using the car's GPS coordinates. A bicycle warning message then is generated containing the position and then broadcast and forwarded by the relay nodes.

A bicycle warning message contains the following information:

- ID: the beacon identity.
- Vehicle ID: vehicle identity.
- Road ID: the identity of the road segment.
- Position: the position of node in (x, y) format. (x, y) is the GPS coordinate.
- Bicycle positions: this field contains the position of bicycles that the car can identify. It is a list that may have multiple position information.
- Timestamp: the timestamp of the beacon.

For the first crash case, the car behind the bicycle will identify it and broadcast its position in the bicycle warning message. The car whose blind spot covers the bicycle thus can know the bicycle position by receiving the warning. As a result, the danger caused by the blind spot is mitigated by cooperative warning system.

Similarly, in the second case, the position of the bicycle will be broadcast by the car behind it, and be received by the car who wants to make left turn. In the third case, the bicycle is identified by a car coming into the intersection from other direction, and the car who is going across the intersection can receive the bicycle position sent by that car.

In this chapter, we assume only one camera is installed in the windshield of a car, therefore, a car can only identify a bicycle in front of it. If more cameras installed on different location of a car can be used (e.g., the camera installed on the back of a car for backward collision warning), the perception range can be increased.

4.5 Performance Evaluation

In this section, we evaluate the performance of our map based protocol. The purpose of the simulation is to see if our protocol can successfully propagate bicycle warning messages to vehicles around an intersection. We assume each vehicle is equipped with a camera and a DSRC device. A bicycle warning message is generated every second, and broadcast by a randomly-chosen vehicle. The more the vehicles can receive the warning message, the better the bicycle-vehicle collision prevention system works.

Since our map based protocol is a multi-hop data dissemination protocol, we compare it with other multi-hop protocols, including Flooding and traditional directional broadcast protocol. Traditional directional broadcast protocol categorizes neighboring cars into 3 groups based on the relative position. The 3 groups are: nodes ahead, nodes behind, and all other nodes. One relay in the forward and backward direction will be selected while all other nodes will be used as relay nodes. The most far away nodes in forward and backward group are selected.

4.5.1 Simulation Model

We choose VanetMobiSim [7] as our traffic generator. It supports IDM_IM (Intelligent Driver Model with Intersection Management) which consider both macro and micro mobility models. IDM_IM defines two intersection scenarios: crossroads regulated by stop signs and road junctions ruled by traffic signals. In our simulations, the intersections are controlled by traffic signals. A node arriving at an intersection is randomly to go to any other directions.

The simulations have been done with ns-3. We used IEEE 802.11 as the underlying protocol with parameters listed in Table 4-1. We create an intersection scenario to run our simulation. We assume that two cars can only connect to each other if they are within each other's line-of-sight.

Table 4-1 Simulation Parameters

Parameters	Value
Simulated area	200m X 200m
Simulated scenarios	Two-way and two lanes
Transmission range	150m
Road width	20m
Speed ranges	40 ~60 km/h
Beacon size	100 Bytes
Bandwidth	6Mbps
Beacon interval	100 ms
Simulation time	100 s

The following metrics are used for performance comparisons:

- Average packet efficient percentage: the number of accepted messages over the number of received messages propagated in the scenario. A message received the first time will be accepted, while the following received duplicate messages will be discarded. During the data dissemination process, multiple relay nodes may rebroadcast messages at the same time, causing the well-known broadcast storm problem. This metric shows the efficiency of the multi-hop data dissemination protocol.

- Reachability: the average of the number of vehicles that accept a message over the number of vehicles that exist in the simulation when a message is propagated. Higher reachability means a protocol can propagate messages reliably and efficiently at intersections.

4.5.2 Simulation Results

Figure 4-6 shows the packet efficiency percentages and reachability. The performance of Flooding drops significantly when node numbers goes higher. As the node density goes higher, the collision becomes a dominate factor of reachability. In Flooding, most of the time messages have to contend in MAC layer which causes more collisions. It occurs less frequently in the traditional directional broadcast protocol. The map based protocol performs much better because of its efficiency, and thus has the best reachability all the time. The reachability of map based protocol is above 80% at all times, which is satisfactory for bicycle-vehicle intersection collision avoidance.

For the packet efficiency, it is not surprised that Flooding performs the worst because it uses all nodes to re-broadcast messages. Traditional directional broadcast protocol is slightly better because it improves packet efficiency by limiting the number of selected relay nodes. The map based protocol performs much better because it select only one relay node for each road segment.

4.6 Conclusions

In this chapter, we propose to use both cameras and DSRC to prevent bicycle-vehicle collisions at intersections. Three common bicycle-vehicle crash cases are targeted. The cameras along with a vision recognition algorithm can detect bicycles and extract position information.

The DSRC devices are used to broadcast bicycle position to neighboring vehicles. In this way, the neighboring cars become “eyes” of the driver, and the collisions can be prevented.

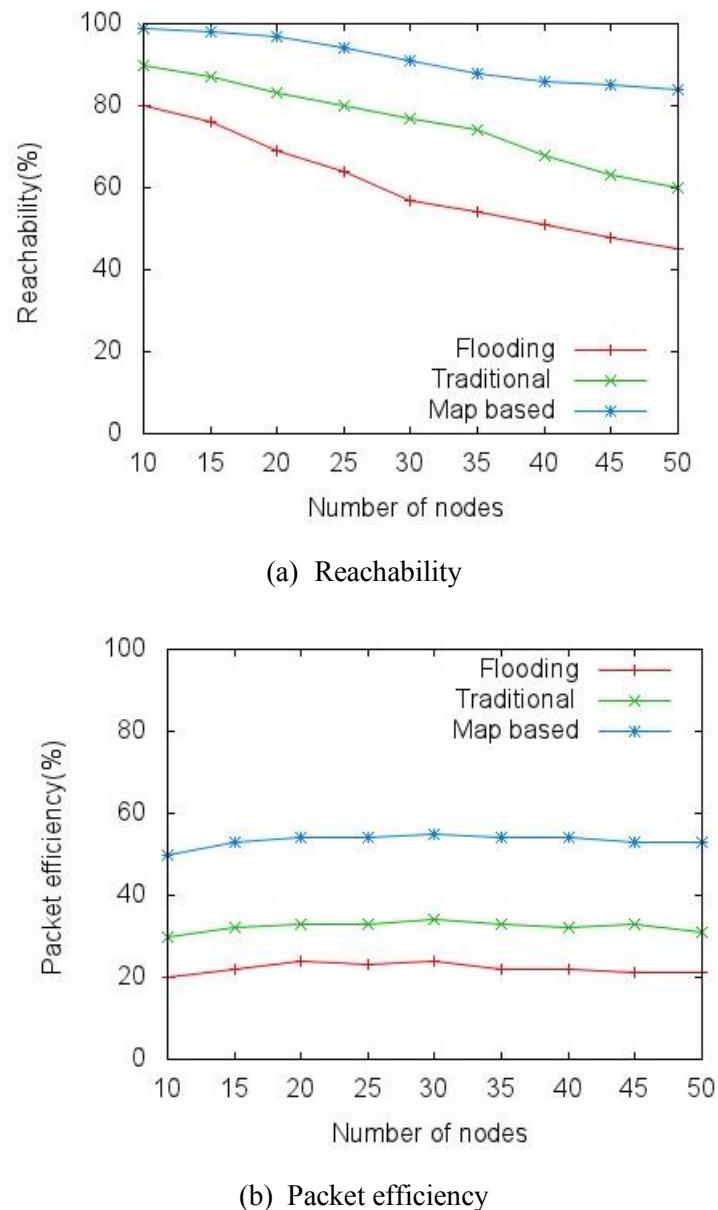


FIGURE 4-6 Reachability and packet efficiency.

Chapter 5 LTE Resource Scheduling for Vehicular Applications

5.1 Introduction

One technology designed for intelligent vehicle system is DSRC (Dedicated Short-Range Communication). It is essentially a distributed solution to intelligent vehicle system. The US Federal Communications Commission (FCC) allocated 75 MHz of spectrum in the 5.9 GHz band for use by ITS vehicle safety and mobility applications. Every vehicle transmits small data packets called Cooperative Awareness Messages (CAMs, also known as beacons, we will use them interchangeably in this chapter) to each other, providing its state such as speed, location, etc. According to the standard of IEEE 802.11p, CAMs are required to be transmitted every 100ms. DSRC offers benefits such as low latency, high reliability and priority access for safety applications [1].

While the usage of DSRC has been widely explored, an alternative, cellular networks, has also been studied. As opposed to DSRC, communication via cellular network is a centralized solution, by which each vehicle connects to a base station to provide its current state. The base station applies collision avoidance algorithm to identify the potential safety hazards and sends warning to those vehicles in danger. The advantage of this approach is, for safety applications such as intersection collision avoidance, communications via cellular network offers better vision in urban environment because the line-of-sight of transmission by DSRC could be easily blocked by buildings around intersections. Also, with the popularity of mobile devices connecting to cellular network, it reduces the cost of integrating these applications into reality.

However, it is not clear if the current cellular network technology can accommodate the amount of traffic generated by CAMs. The state of art technology, LTE, offers as high as 50 Mbps uplink data rate and 100 Mbps downlink data rate. It can be operated on 1.4 – 20 MHz bandwidth. For intersection collision avoidance, the amount of traffic generated by CAMs can be determined by a number of factors: the cell size, the number of intersection per cell, the number of vehicles per intersection per cell, the size of CAM, and the transmission interval. The cell size in LTE can be up to tens of kilometers. Assuming a typical cell size of 5km is used, and there are 10 intersections in a cell, 50 vehicles at each intersection, 5,000 CAMs are generated per second if each vehicle transmits CAMs at 10 Hz. If adaptive beaconing is used, the number of CAMs generated can be reduced [28][29].

Generally, CAM messages can be transmitted in two ways: via random access or via dedicated communication. In random access approach, a UE accesses the base station for every CAM transmission. Random access offers the benefit of fully channel diversity and it is suitable for adaptive beaconing, but it incurs more signaling overhead. On the contrary, in dedicated communication approach, CAMs are transmitted via dedicated channel. Since resources are pre-allocate, dedicated communication reduces signaling overhead, but how resources should be scheduled for transmitting CAMs is not well investigated. Persistent scheduling may be suitable for the regularly transmitted CAMs, but if adaptive beaconing is used, it may not be easy to estimate the number of CAMs generated accurately. Thus persistent scheduling may not work well in this case.

In this chapter, we compare and analyze the performance of two approaches in terms of bandwidth capability. Additionally, we will discuss the effect of radio resource scheduling algorithms on CAM transmissions. We propose a semi-adaptive beaconing method for semi-scheduling and analyze its bandwidth capability. We expect our research provides a

direction to cellular network resource allocation for this specialized transmission pattern to enhance the experience of vehicular applications.

5.2 Cam Delivery Methods

To transmit CAMs, a User Equipment (UE) has to either access a base station via random access channel (Physical Random Access CHannel, PRACH) for uplink resource grant, or already keep a connection with a base station. In the latter case, CAMs can be transmitted on the dedicated channel – Physical Uplink Shared CHannel (PUSCH). Which one will be used – random access or dedicated connection – depends on the state of a UE. In LTE, a UE can be either in idle state or in connected state. In idle state, a UE performs cell selection or cell reselection procedure, i.e., it decides on which cell to camp. It also monitors a paging channel to detect incoming calls. Random access approach can be used in transition from idle station to connected state, for example, to setup an outgoing call. It can also be used when a UE is in connected state but has lost uplink synchronization, intending to regain synchronization for new data transmission. The regularly transmitted CAMs will keep a UE in connected state; however, if a context aware scheduling is used by a base station, the random access method can be applied as well.

There are two forms of random access procedure in LTE, contention-based and contention-free. Contention-based random access procedure is designed to be a four phase process. In phase one, a preamble signature is randomly chosen by each UE, leading to the possibility of signature collision when two UEs transmit the same signature. In phase two, the base station sends random access response containing a timing alignment instruction to synchronize subsequent uplink transmissions from the UE, and an initial uplink resource grant for transmission of the phase 3 message. Then the actual random access message (L2/L3

message) can be transmitted in phase 3, conveying information such as scheduling request. In the case of preamble signature collision in phase one, both UEs will transmit their L2/L3 messages. This may result in no messages can be decoded successfully by the base station, and the messages will be retransmitted by Hybrid Automatic Repeat request (HARQ); or one of the messages can be decoded and the contention will be resolved in phase four. In phase four, the base station sends contention resolution message containing the UE identity. The UE which finds its own identity will send back ACK, while others will send nothing back. The contention-free procedure can be used when low latency is required such as handover, by assigning a dedicated signature to a UE. Several preambles will be reserved for this purpose. It is not likely to use all reserved preambles for CAM transmission. In this chapter, we only consider contention-based random access regarding CAM delivery.

If the preamble is not successfully transmitted, a UE increases the transmission power for retransmission. This is called power ramping. Since the preambles are orthogonal to each other, the interference is reduced. Therefore it is not as important as in WCDMA to keep the initial power low to avoid interference. The likelihood of successful initial preamble transmission is increased.

The CAMs can also be transmitted via PUSCH. In LTE, the uplink bandwidth is used by several physical channels – Physical Uplink Control Channel (PUCCH), PUSCH, and PRACH. PUCCH is always allocated on the two edges of bandwidth while PUSCH is placed in the central band, in order to maximize the frequency diversity and achievable PUSCH data rate. It also facilitates data scheduling on PUSCH due to wider bandwidth of PUSCH. The number of Resource Blocks (RBs) used by PUCCH depends on the system bandwidth. Typical numbers would be 2 RBs for 1.4 MHz, 8 RBs for 5 MHz, 16 RBs for 10 MHz, on a per subframe basis. The PRACH is time-frequency multiplexed with PUSCH. There are several PRACH configurations: one slot (1ms) is allocated per 10ms for 5MHz bandwidth, two for

10MHz, and three for 20MHz. The typical bandwidth of PRACH in frequency domain is 6 RBs [30].

The benefit of random access approach is that it can fully exploit the frequency and channel diversity. A UE can be allocated transmission resource applicable to the current channel condition. Another advantage is that, when adaptive beaconing by which the CAM message is generated and transmitted based on the vehicle state such as speed, is used by a UE, it is better to use random access since it is not easy to reserve resource accurately for adaptively generated CAMs.

The main drawbacks of random access approach are the signaling overhead and longer latency. The random access approach incurs more signaling overhead given the four phase access scheme. The latency requirement of accessing base station via dedicated channel is less than 10ms, while that of random access is less 100ms [30]. In addition, the bandwidth capacity of random access and dedicated connection is not well investigated. An analysis of bandwidth capacity of both approaches is given in the last section of this chapter.

5.3 Resource Scheduling

LTE uses OFDMA (Orthogonal Frequency-Division Multiple Access) as the multiple access technology. Multiple access is achieved by assigning subcarriers to individual users. In LTE, the total bandwidth is divided into Resource Blocks (RBs) in the frequency domain. Each RB contains 12 subcarriers and each subcarrier is 15 kHz. In time domain, LTE defines 10ms frame which is further divided into 1ms subframe. Each subframe contains two slots in 0.5ms length. Each RB corresponds to one slot in time domain. Data are transmitted in units known as Transport Blocks(TB), each of which is passed down per Transmission Time Interval (TTI), where a TTI is 1ms, corresponding to one subframe duration. TB corresponds to MAC Protocol

Data Unit (PDU); it is the minimum unit for scheduling purpose. To improve the scheduling performance, frequency selective scheduling can be used by which specific frequency is selected for transmission based on the channel estimation by uplink reference signaling. In the case where reference signaling is not available or the signaling overhead is intended to be avoided, the frequency diversity can also be achieved by frequency hopping either within a subframe or between subframes.

The physical layer in LTE supports HARQ on the physical downlink and uplink shared channels, with separate control channels to send the associated acknowledgement feedback. In uplink, HARQ is synchronous – the retransmissions occur at predefined times relative to the initial transmission. Therefore, there is no need to signal information such as HARQ process number.

The traffic pattern of CAM transmission is that, every short period of time (100ms), a small data packet is sent. This is similar to VoIP traffic, where a voice packet arrives every 20ms. Therefore, it is reasonable to schedule CAM messages in the similar way as VoIP packets. Generally there are three scheduling methods proposed for VoIP [31][32][33]:

5.3.1 Dynamic Scheduling

In dynamic scheduling, UE sends resource request message to base station for every data packet. Each packet can be scheduled by L1/L2 signaling through PUSCH/Dedicated Control Channel (DCCH). It achieves channel diversity in both time and frequency domain, but also incurs much signaling overhead. For CAM transmission, the number of control channel needed can be estimated as follows [31]:

$$N_{CCH} = nm\lambda\tau \quad (5-1)$$

- 83 -

n is the number of vehicles per intersection, m is the number of intersections per cell, λ is the average number of transmissions needed (including retransmissions), τ is the inter-arrival frequency for CAMs which is 10 Hz. Suppose $n=50$, $m=10$, the average number of transmissions is 1.2, based on Eq.(5-1), 6 control channels are needed per TTI.

5.3.2 Persistent Scheduling

Persistent scheduling means that a sequence of resource blocks is allocated at the beginning of transmission. The resource blocks are reserved for pending data (re)transmissions. The allocation also includes the resource for HARQ retransmissions. The advantage is that it is simple and requires less signaling overhead. However, to reserve resources for HARQ leads to resource waste if transmissions success and therefore no retransmission is needed; the reserved resource blocks will not be able to be used by other users.

5.3.3 Semi-persistent Scheduling

Seeing the drawbacks of dynamic scheduling and persistent scheduling, semi-persistent scheduling uses both scheduling methods: persistent scheduling for initial transmission and dynamic scheduling for retransmissions. At the beginning of transmission, a UE sends an uplink resource request to a base station. Upon receiving resource request, the base station can allocate a predefined sequence of resource blocks to the UE. The UE can therefore transmit data using these resource blocks. The base station can also reallocate different resources or reassign different transport format to enable link adaptation if needed. The persistent resource allocation can be repeated every 100ms (the inter-arrival time of CAMs) until it is not needed (e.g., a user moves out of an intersection). The retransmission will be allocated dynamically in the vacant resource blocks using L1/L2 control channel signaling. If most transmissions are successful,

semi-persistent scheduling avoid resource waste in persistent scheduling, and signal overhead in dynamic scheduling.

In summary, the relation between LTE resource scheduling for CAM transmission can be stated as follows: among these three approaches, dynamic scheduling is suitable for adaptive beaconing because it is able to dynamically allocate resources for adaptively generated CAMs. On the contrary, persistent scheduling and semi-persistent scheduling can work well for CAMs with fixed beaconing rate. Because the performance of resource scheduling depends on the traffic pattern, we argue that how beacons are generated should be taken into account when developing new resource scheduling method for vehicular applications.

5.4 Semi-Adaptive Beaconing for Semi-Persistent Scheduling

In general, persistent scheduling is suitable for CAM transmissions, since CAMs are transmitted regularly every 100ms. If adaptive beaconing is used, dynamic scheduling becomes a better candidate because the inter-arrival time may vary and it is not easy to accurately reserve radio resource. In this case, random access may also be applied. However, in intersection collision avoidance use case, a semi-adaptive beaconing approach can be used together with semi-persistent scheduling. Since CAMs can be generated based on the movement of vehicle, it is possible to simplify the vehicle movement at an intersection into two states: moving or stopping. In moving state, a vehicle keeps sending CAM to base station, until it stops to wait for red light. As soon as it starts moving again, it sends resource request to base station for CAM transmissions.

We assume each UE has GPS so that it knows when it approaches an intersection. The CAM transmission from a UE to a base station makes UE stays in connection state, resulting

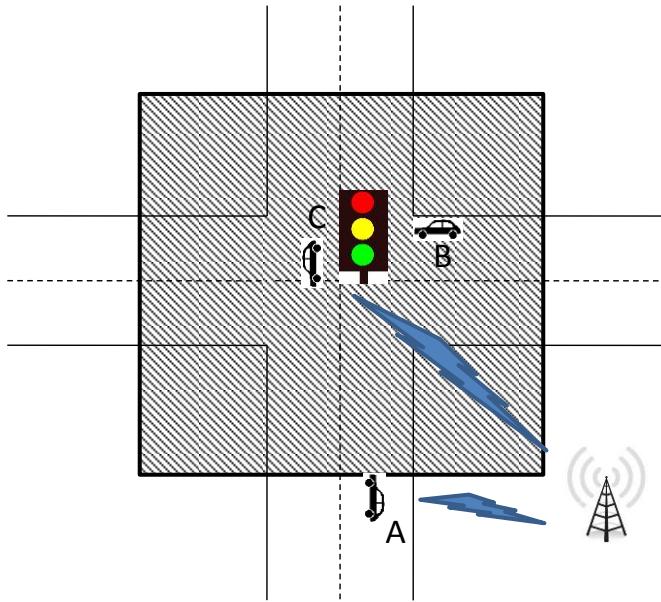


FIGURE 5-1 Vehicle a starts to send cams to the base station when entering an intersection. Vehicle b stops sending cams because it is waiting for red light. Vehicle c keeps sending cams because it is going through the intersection.

in considerable power consumption. We assume that UEs can get plenty of power supply from vehicles. When a vehicle approaches an intersection, the UE sends scheduling request via random access for initial connection setup. When the base station receives the request, it schedules resource blocks for CAM transmissions every 100ms. The retransmissions will be scheduled dynamically using HARQ as it is a semi-persistent scheduling. When a vehicle stops at an intersection to wait for red light, it stops sending CAMs. The base station can therefore reschedule the resource for other users. The UE start sending CAMs again as soon as it moves again, until it moves out the intersection area. Figure 5-1 shows an example of this.

5.5 Performance Analysis

In this section, we analyze the capacity of random access and dedicated connection, and compare the performance of them with difference configurations.

There are 64 preamble signatures in one PRACH resource, each of which is transmitted in 1ms subframe. Depending on the PRACH configuration, different numbers of PRACH resources can be allocated in one frame (10ms). One PRACH resource is allocated for a typical 5MHz frequency band. For simplicity, assuming all preambles can be used for random access, the capability of random access in terms of how many accesses can be handled can be calculated as follows [34]:

$$\frac{1000ms}{10\frac{ms}{frame}} \times 1\frac{subframe}{frame} \times 64\frac{preambles}{subframe} = 6400\frac{preambles}{s}$$

In [34], the authors assume the ramping factor is 2, the decode error rate is 0.3, the collision factor is 0.3, and thus the number of random accesses a base station can handle per second is:

$$\frac{6400}{2} \times 0.7 \times 0.7 = 1568\frac{Accesses}{s}$$

There are roughly 1500 accesses can be supported per second. If there are 10 intersections per cell, 50 vehicles per intersection, and 3 CAMs are transmitted per second because of the usage of adaptive beaconing, the number of CAMs transmitted per cell per second is: $10*50*3=1500$ CAM/cell·second. In this configuration, PRACH can roughly handle the CAM traffic. Note that this can be regarded as the maximum random access capacity per second; the actual random accesses which PRACH can handle depends on the channel condition as well.

Table 5-1 shows the number of users can be supported in different PRACH configurations.

TABLE 5-1 THE NUMBER OF SUPPORTED USERS BY RANDOM ACCESS (3HZ BEACONING RATE)

	# of RA resource per frame	# of preambles per sec	# of accesses per sec	# of users per sec
1.4 MHz	0.5 (1 RA resource per 20 ms)	3200	784	261
5 MHz	1	6400	1568	522
10 MHz	2	12800	3136	1045
15 MHz	3	19200	4704	1568
20 MHz	5	32000	7840	2613

In theory, the capacity of dedicated connection can be estimated as follows:

$$R_{avail} = N_{CAM} R_{CAM} (1 + \lambda_{re} \varepsilon_{re}) \quad (5-2)$$

where R_{avail} is the number of available uplink RBs, N_{CAM} is the number of CAMs, R_{CAM} is the number of RBs needed per CAM message, λ_{re} is the number of retransmissions, and ε_{re} is the ratio of the number of RBs needed for retransmission to that of initial transmission. Note that here we assume all available resources can be used for CAM

transmissions. To estimate the capacity, we need to know further details of each parameter. R_{avail} can be estimated as follows:

$$R_{avail} = R_{PUSCH} = R_{total} - R_{PUCCH} - R_{PRACH} \quad (5-3)$$

where R_{PUSCH} is the number of available RBs on PUSCH for data transmission, R_{total} is the total number of uplink RBs, R_{PUCCH} is the number of RBs of PUCCH, and R_{PRACH} is the number of RBs of PRACH. All these parameters depend on the resource configuration. Considering the typical 5 MHz bandwidth, 8 RBs are used for PUCCH per subframe. One PRACH slot is allocated per frame, and one PRACH slot is 1ms and occupies 6 RBs in frequency domain. Due to the spectrum allocation overhead, only 25 RBs are useable in 5 MHz band. As a result, R_{total} in a frame equals to $25 * 2$ RBs/subframe * 10 subframe/frame = 500 RBs/frame. R_{PUCCH} equals to 8 RBs/subframe * 10 subframe/frame = 80 RBs/frame. R_{PRACH} equals to $6 * 2$ RBs/subframe * 1 subframe/frame = 12 RBs/frame. R_{avail} equals to $500 - 80 - 12 = 408$ RBs/ frame. Table 5-2 shows the number of available RBs in different configurations.

TABLE 5-2 THE NUMBER OF AVAILABLE RBs

	# of RBs in frequency domain	Total # of RBs per frame	# of RBs of PUCCH per frame	# of RBs of PRACH per frame	# of available RBs per frame
1.4 MHz	6	120	20	3	97

	# of RBs in frequency domain	Total # of RBs per frame	# of RBs of PUCCH per frame	# of RBs of PRACH per frame	# of available RBs per frame
5 MHz	25	500	80	12	408
10 MHz	50	1000	160	24	816
20 MHz	100	2000	320	60	1620

To get the value of R_{CAM} , we have to know the size of CAM and the number of bits a RB can hold. The latter depends on the modulation scheme. If 64QAM is used, each OFDM symbol can represent 6 bits. If QPSK is used, each OFDM symbol can represent 2 bits. In each 1ms subframe (2 RBs), 2 symbols are reserved for uplink reference signaling. Therefore, one subframe can hold at least $(7\text{symbol}*2-2)*2*12 = 288 \text{ bits} = 36 \text{ bytes}$. Assuming each CAM contains the ID of vehicle (32 bits), the position of vehicle (GPS coordinates, latitude and longitude are double-precision 64-bit floating points resulting in total 128 bits) and headers, and further assume the security check is done by SIM module and thus is omitted here, one subframe should be sufficient to accommodate one CAM.

The number of CAMs generated per second can be determined by the number of vehicles per intersection, the number of intersections per cell, and the CAM transmission frequency, i.e.:

$$N_{CAM} = \alpha_{avg} nmf \quad (5-4)$$

n is the number of vehicles per intersection, m is the number of intersections per cell. f is the CAM generation rate which is 10 Hz. α_{avg} is the average ratio of moving time to total time when a vehicle is in intersection area. Assume $\varepsilon_{re} = 1$ which means retransmissions use the same resource as the original transmission, $R_{CAM}=2$, Eq. (5-2) can be represented as:

$$R_{avail} = 2\alpha_{avg}nmf(1 + \lambda_{re}) \quad (5-5)$$

If $f = 10$, the number of supported users is:

$$nm = \frac{R_{avail}}{20\alpha_{avg}(1 + \lambda_{re})} \quad (5-6)$$

Assuming $\lambda_{re} = 0.2$ and $\alpha_{avg} = 1$ (i.e., CAMs are not generated adaptively), 1700 users can be supported per second in 5 MHz band. If α_{avg} equals to 0.5 (i.e., a vehicle at an intersection is moving half of the time,), then 3400 users can be supported. Table 5-3 shows the number of users can be supported via dedicated connection. Figure 5-2 and Figure 5-3 show the results for different values of λ_{re} and α_{avg} .

TABLE 5-3 THE NUMBER OF SUPPORTED USERS VIA DEDICATED CONNECTION

	# of available RBs per frame	# of users per sec ($\lambda_{re} = 0.2$)	
		$\alpha_{avg} = 1$	$\alpha_{avg} = 0.5$
1.4 MHz	97	404	808
5 MHz	408	1700	3400
10 MHz	816	3400	6800
20 MHz	1620	6750	13500

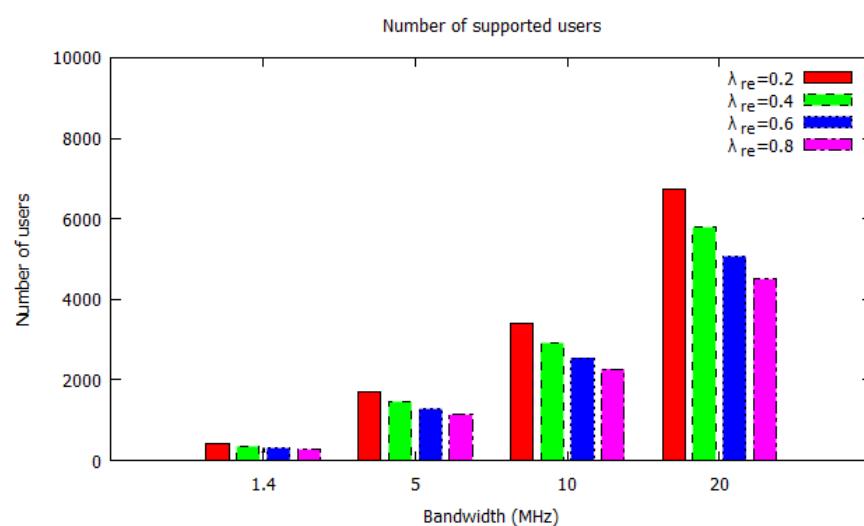


FIGURE 5-2 Number of supported users ($\alpha_{avg} = 1$)

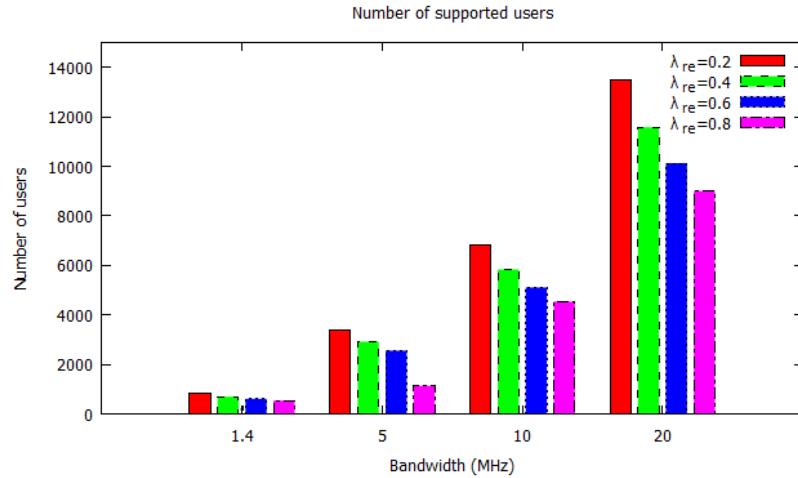


FIGURE 5-3 Number of supported users ($\alpha_{avg} = 0.5$)

In the above analysis, the number of available resources depends on the resource configuration. Alternatively, we can estimate the spectrum efficiency. The number of available RBs per MHz (6 RBs) is: 6 RBs/subframe * 2 subframe/frame * 1000 frame/s = 12000 RBs/s. Assuming $\alpha_{avg} = 1$ and $\lambda_{re} = 0.2$, based on Eq. (5-6), the number of users can be supported per MHz is 500 users/sec·MHz. Table 5-4 shows the spectrum efficiency for different values of λ_{re} and α_{avg} .

TABLE 5-4 THE NUMBER OF SUPPORTED USERS PER SEC·MHZ

	# of supported users per sec·MHz	
λ_{re}	$\alpha_{avg} = 1$	$\alpha_{avg} = 0.5$
0.2	500	1000
0.4	428	856
0.6	375	750
0.8	333	666
1	300	600

It is obvious that using dedicated connection achieves better capacity, even though adaptive beaconing is considered (3Hz CAM generation rate is used) for random access. Random access may or may not be able to support the CAM traffic (depending on the number of users and the transmission frequency), but dedicated connection is capable of that given 1 MHz bandwidth is assigned for CAM transmission. The semi-adaptive beaconing approach can reduce the amount of CAMs generated by the factor α_{avg} , and thus increase the capacity. In other words, fewer resources are needed for CAM transmissions. If $\alpha_{avg}= 0.5$, the capacity can be doubled. Semi-adaptive beaconing is simple yet effective, increasing the capacity significantly.

5.6 Conclusions and Future Works

In this chapter, we analyzed and compared the capacity of random access and dedicated connection for CAM transmission. Although the resource configurations may vary (depends on real deployment), it is shown that the dedicated connection can support 2 to 3 times of users than random access can. Furthermore, we proposed a semi-adaptive beaconing approach suitable for semi-persistent scheduling for CAM transmission based on the state of vehicle. If semi-adaptive beaconing is applied, the capacity can be increased by the factor $1/\alpha_{avg}$. The semi-adaptive beaconing provides a simple yet effective way for CAM transmission.

The semi-adaptive method we proposed in this chapter is a naive approach – we only distinguish between moving and stopping state of vehicle. A more sophisticated approach may be applied to improve the degree of adaptiveness of this approach by considering vehicle movement in finer granularity, such as adaptively transmitting CAMs based on the speed of vehicle. In this way, the faster a vehicle moves, the more the CAMs transmitted, and vice versa.

It is up to future study to see if it is needed to allocate a dedicated bandwidth for CAM transmission, or multiplex it with other data. Assigning a dedicated bandwidth for CAM transmission avoids the interference and resource competition from other user data which may be critical for vehicular safety applications, but it decreases the resource utilization because the resources will not be able to be used by other data.

What has not been covered in this chapter was the financial problem. Transmitting CAMs results in extra bandwidth consumption which may not be acceptable by network operators given the fact that radio resource is scarce today, unless users are willing to pay for it. We expect more researches could be done in this area to create incentives to real deployment.

Chapter 6 A Simulation Study of Beacon Transmission Using LTE

6.1 Introduction

LTE is proposed as an alternative to DSRC. Unlike the direct point to point transmissions in DSRC, the communications using LTE are controlled by base stations. Because base stations are usually mounted on the top of the buildings, LTE excels DSRC on the coverage in the urban area. This is especially useful for certain applications such as intersection collision avoidance service, when the communications of DSRC could be blocked around intersections.

One problem of using LTE on VANET applications is whether the LTE bandwidth can support the beacon traffic. It is not possible to evaluate the LTE channel capability in the scale as large as the city dimension. To this end, simulation is the only way to test the validity of this approach at the current stage.

Aiming on this, in this chapter, we explore the possibility of using LTE for vehicular safety applications by simulations. The LTE-EPC Network Simulator (LENA) [40] is a LTE module based on the open source Network Simulator (NS-3) [41] for network systems. The current stage of NS-3 offers most of network components and protocols for both wire and wireless communications. Building on top of NS-3, the LENA project provides the LTE module for evaluations on LTE. Combined with NS-3, it is convenient to run simulations for LTE performance evaluation.

We conduct simulations to evaluate the performance of LTE uplink, downlink, dual-link, as well as DSRC in terms of delivery rate and delay. We also take into account the real application

– intersection collision avoidance service, and evaluate the performance in intersection scenario. The results show that the LTE can offer satisfactory performance for safety applications with limited number of nodes.

This chapter is organized as follows. In section 6.2, we briefly introduce the background and related works of DSRC and LTE regarding beacon transmissions. The detail of performance evaluation is elaborated in section 6.3, followed by the study of real application scenario in section 6.4. We provide the conclude remark at the end of this chapter.

6.2 Background and Related Works

6.2.1 Dedicated Short-Range Communication (DSRC)

DSRC is specifically designed for high-speed vehicle communications. Compared to Wi-Fi, DSRC operates in a 75 MHz licensed spectrum around 5.9 GHz, avoiding potential uncontrollable interference in Wi-Fi frequency band. In addition, the physical layer parameters are optimized for outdoor transmissions while those of Wi-Fi are optimized for indoor transmissions. It also provides priority access which is not part of the Wi-Fi standards [35].

The main drawbacks of DSRC regarding vehicular safety applications are:

1. The beacon delivery is not reliable when node density is high. This is due to the fact that each vehicle has to contend for the channel and collisions are inevitable in wireless broadcast environment.
2. The line-of-sight communication could be blocked in urban environment by buildings. This may be a problem for certain safety applications such as intersection collision avoidance service.
3. Due to the cost, the deployment of Road-Side Unit (RSU) has been indefinitely postponed.

The underlying protocol of DSRC is 802.11p. We will use 802.11p and DSRC interchangeably in the rest of this chapter to represent the distributed communication solution to vehicular safety applications if no confusion is incurred.

6.3 Long Term Evolution (LTE)

LTE uses OFDMA (Orthogonal Frequency-Division Multiple Access) as the multiple access technology. Multiple access is achieved by assigning subcarriers to individual users. In LTE, the total bandwidth is divided into Resource Blocks (RBs) in the frequency domain. Each RB contains 12 subcarriers and each subcarrier is 15 kHz. In time domain, LTE defines 10ms frame which is further divided into 1ms subframe. Each subframe contains two slots in 0.5ms length. Each RB corresponds to one slot in time domain. Data are transmitted in units known as Transport Blocks(TB), each of which is passed down per Transmission Time Interval (TTI), where a TTI is 1ms, corresponding to one subframe duration [30].

6.4 LTE Beacon Delivery Methods

To transmit Beacons, a User Equipment (UE) has to either access a base station via random access channel (Physical Random Access CHannel, PRACH) for uplink resource grant, or already keep a connection with a base station. In the latter case, Beacons can be transmitted on the dedicated channel – Physical Uplink Shared CHannel (PUSCH).

The benefit of random access approach is that it can fully exploit the frequency and channel diversity. A UE can be allocated transmission resource applicable to the current channel condition. Another advantage is that, when adaptive beaconing by which the beacon message is generated and transmitted based on the vehicle state such as speed, is used by a UE, it is better to use random access since it is not easy to reserve resource accurately for adaptively

generated Beacons. The main drawbacks of random access approach are the signaling overhead and longer latency. The random access approach incurs more signaling overhead given the four phase access scheme.

Which one will be used – random access or dedicated connection – depends on the state of the UE. In LTE, a UE can be either in idle state or in connected state. In idle state, a UE performs cell selection or cell reselection procedure. Random access approach can be used in transition from idle station to connected state, for example, to setup an outgoing call. It can also be used when a UE is in connected state but has lost uplink synchronization, intending to regain synchronization for new data transmission. The regularly transmitted beacons will keep a UE in the connected state; therefore In this chapter, we assume UEs are in connected state when beacons are transmitted.

6.5 LTE Capability of Beacon Transmissions

Several researches have been done to investigate the possibility of using LTE for vehicle safety applications. In [34], the authors investigate and compare the number of beacons supported of DSRC, Universal Mobile Telecommunications System (UMTS), and LTE. Delay of transmitting beacons via random access or dedicated connection is also analyzed from the perspective of design. The authors argue that the cellular communication technology may not provide the same awareness update rate and latency as DSRC.

Our previous research analyzed and compared the capacity of random access and dedicated connection for beacon transmissions [42]. Although the LTE resource configurations may vary (depends on real deployment), it is shown that the dedicated connection can support 2 to 3 times of users than random access can. In addition, the delay of random access is much longer than dedicated connection due to the 4-phase content-based access procedure.

The above researches analyze the capacity of LTE for beacon transmissions based on the design and configurations. It is up to future simulations or experiments to figure out the actually capacity within which the LTE can provide satisfactory performance, namely the delivery rate and delay.

6.6 Performance Comparison

In this section, we evaluate the performance of LTE for beacon transmissions. We first introduce the schemes we use in our simulations, and then elaborate the metrics and the simulation settings. We finally present the simulation results in the end of this section.

6.6.1 Schemes

We conduct simulations for both 802.11p and LTE. 802.11p is evaluated as a comparison to LTE schemes. For LTE schemes, we assume each UE is connected to the base station throughout the simulation, since the regularly transmitted beacons will keep the UE in the connected state. This may result in excessive power consumption. We assume that UEs can obtain plenty power supply from vehicles. The following schemes are used in our simulations:

- 1) *802.11p*: 802.11p is an amendment to IEEE 802.11 standard, designed specifically for transmissions between high-speed vehicles. Beacons are broadcast to surrounding vehicles in this scheme.
- 2) *LTE uplink*: in this scheme, we evaluate the LTE uplink performance. A remote server is setup to receive beacons transmitted by each UE. A UDP server is installed on the remote server while a UDP client is installed on each UE. Beacons are transmitted every 100 ms.

- 3) *LTE downlink*: in this scheme, we evaluate the LTE downlink performance. A remote server is setup to send beacons to every UE every 100 ms. For each UE, a UDP client is installed on the remote server. A UDP server is installed on each UE to receive beacons.
- 4) *LTE dual-link*: simply evaluate the LTE performance unilaterally is not realistic. In real world, the uplink and downlink connections co-exist at the same time. In this scheme, a UDP client/server is installed on each UE to send/receive beacons to the remote server. The remote server has a UDP server to forward each beacon to every other UE as soon as it is received from the source UE. To forward beacon to every other UE may be unnecessary; in fact, only the UEs in the vicinity of the source UE need to receive its beacons, however, it shows how LTE performs in the extreme case.

6.6.2 Metrics

The purpose of transmitting beacons is to deliver the position information to the surrounding vehicles, so that each vehicle can take actions to prevent possible collisions. As a result, it is important if beacons can be successfully delivered to intended receivers. For network simulations, the most often used metrics are the delivery rate and delay. The delivery rate is usually defined as the ratio of received packets to transmitted packets. However, it is not very suitable for our simulation because it is usually used on end-to-end connections. For beacon delivery, a single beacon transmission is supposed to be received by multiple receivers. Due to this reason, we define the delivery rate as follows:

- *The delivery rate*: for 802.11p, it is defined as the ratio of the number of beacons received to the number of the intended receivers, i.e., the surrounding vehicles within the transmission range each time a beacon is sent. For LTE, the definition depending on each scheme: in uplink and downlink schemes, the delivery rate is defined as the ratio of the number of received beacons to the number of transmitted beacons. In dual-link

scheme, it is defined as the number of received beacons to the number of forwarded beacons

In addition, the delay is defined as follows:

- *The delay*: it is defined as the time from a beacon is generated to the time it is received by a receiver.

6.6.3 Simulation Settings

We use LENA as our network simulator. At the beginning of the simulation, each UDP client starts to send beacons randomly within 1 second. After that, beacons are transmitted regularly every 100 ms. For LTE schemes, we assume that the remote server is connected to PDN GateWay (PGW) with a dedicated link. Therefore, the delay between PGW and the remote server is omitted in our simulations.

The simulation layout is 2000 m by 40 m. This is equivalent to the layout of a highway road segment. The UEs are placed evenly in the road layout. The LTE base station is installed at the location (1000, 0), the center of the road topology. Table 6-1 shows the simulation parameters.

TABLE 6-1 SIMULATION PARAMETERS

Simulation Parameters	Value
Simulated Area	2000 m × 40 m
Packet size	100 bytes
802.11p	Value

Simulation Parameters	Value
Parameters	
Modulation	OFDM
Tx Power	16 dBm
Date Rate	6 Mbps
Transmission Range	100 meters
Tx Gain	1 dB
Rx Gain	1 dB
LTE Parameters	Value
Base Station Tx Power	46 dBm
UE Tx Power	23 dBm
Bandwidth	5 MHz (25 RBs)
Scheduling Algorithm	Proportional Fair

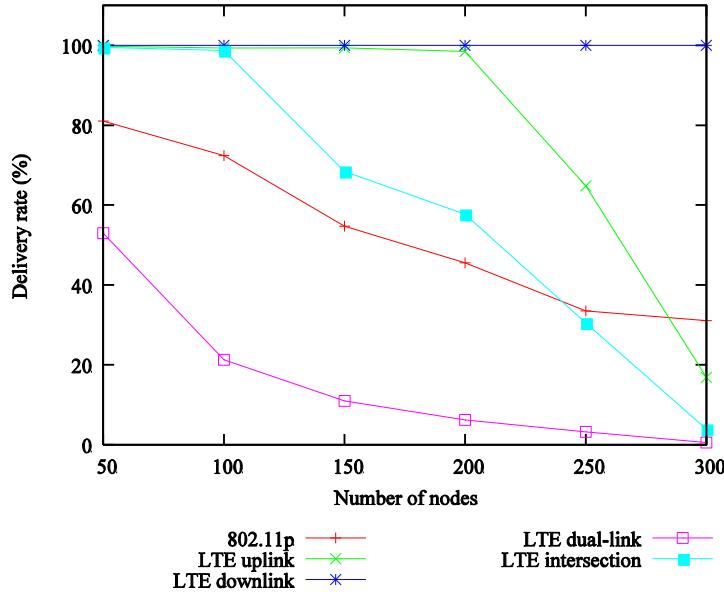


FIGURE 6-1 Delivery rate.

6.6.4 Results

Figure 6-1 shows the result of the delivery rate. As we can see in Figure 6-1, the delivery rate decreases as the number of nodes increases. The delivery rate of 802.11p is from 50% (300 nodes) to 80 % (50 nodes). In LTE downlink scheme, the delivery rate is perfect – 100 % in all cases. In LTE uplink schemes, the delivery rate is about 100 % when the number of nodes is below a certain threshold. After the number of nodes exceeds the threshold, the delivery rate drops quickly. This phenomenon indicates that the radio resource is not sufficient to handle the beacon traffic and thus the packet loss rate increases. For LTE uplink scheme, the threshold is about 200 nodes. The observation that the downlink can support much more nodes than the uplink is consistent to the asymmetric uplink/downlink data rate of LTE. The peak data rate of

downlink and uplink can be up to 300 Mbps and 75 Mbps, respectively (with 4X4 MIMO using 20 MHz spectrum) [30].

However, the delivery rate of LTE dual-link is much less than uplink or downlink. It is not surprising though, because each beacon has to be forwarded to every other node. The beacon traffic of dual-link is proportional to the square of the number of nodes. The number of forwarded beacons can be calculated as follows:

$$N_{total} = nN_{nodes}(N_{nodes} - 1) \quad (6-1)$$

Where N_{total} is the number of beacons forwarded by the base station, n is the number of beacons transmitted by each UE, N_{nodes} is the number of nodes.

Figure 6-2 shows the result of average delay. As we expect, 802.11p broadcast transmission incurs the lowest delay since beacons are only broadcast to one-hop neighbors. The delay is as low as just several milliseconds. On the contrary, beacons have to be forwarded by the base station in LTE schemes and thus experiences longer delay. Beacons have to go through the following process to be received by cluster heads:

1. Beacons are transmitted to the base station from the senders.
2. Beacons are received by the base station as the order scheduled by the system scheduler.
3. Beacons go up the LTE protocol stack Medium Access Control (MAC)/ Radio Link Control (RLC)/ Packet Data Convergence Protocol (PDCP).
4. The server decides to whom to forward the beacons.
5. Beacons go down the LTE protocol stack.
6. Beacons are scheduled for transmission.
7. Beacons are received by the target vehicles.

When the number of nodes is high, the delay could be more than 100 ms. However, the delay drops after the number of nodes reaches about 200. Combined with the delivery rate results, it shows the radio resource is depleted and most packets are simply discarded.

In addition to the average delay, the maximum delay may be more meaningful for safety

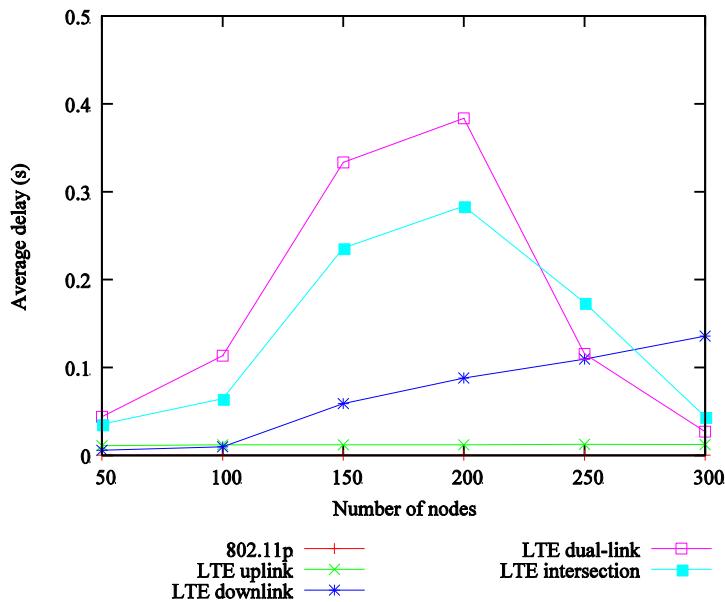


FIGURE 6-2 The average delay.

applications. We can see the maximum delay in Figure 6-3. The maximum delay of LTE schemes can be more than hundreds of milliseconds as the number of nodes grows, which is not acceptable for safety applications. To keep the delay at the acceptable level, it is suggested that the number of nodes should not exceed 100.

From our simulation results, we made several observations:

1. Although 802.11p is specifically designed for high-speed vehicle environment, it does not guarantee the successful beacon delivery even in low node density. It is due to the fact that 802.11p is a distributed solution where no delivery guarantee assumption is the basic. The performance of LTE is very satisfactory in terms of delivery rate due to the predetermined scheduling of transmission set by the system scheduler, when the number of nodes is within the threshold.
2. Because the LTE downlink can support much higher data rate than uplink, therefore the uplink will be the bottle neck for beacon transmission.

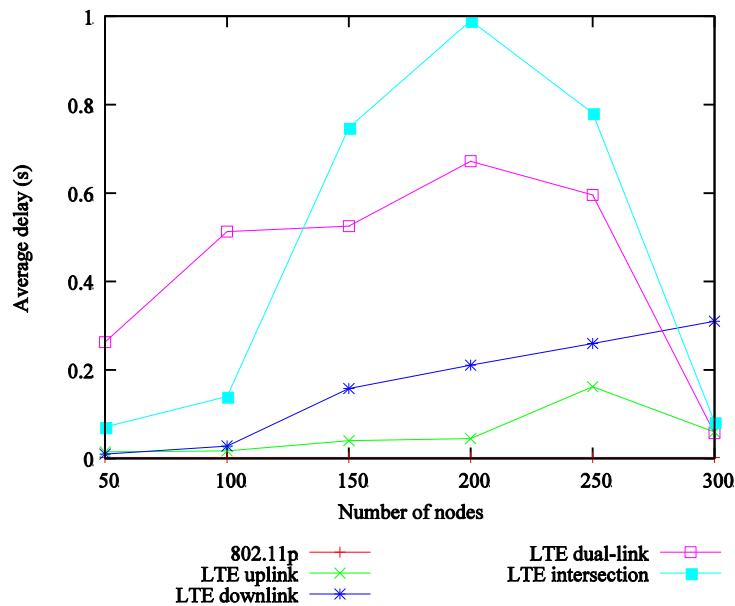


FIGURE 6-3 The maximum delay.

3. The delay of LTE is much longer than 802.11p. In 802.11p scheme, the transmissions are one-hop ad-hoc transmissions. Therefore, LTE is not possible to reach the same performance level of 802.11p in terms of delay. However, LTE can still provide satisfactory delay (100 ms) within the node number threshold (100 nodes).

6.7 Performance Evaluation of Intersection Collision Avoidance Service

Simply conducting simulations on LTE uplink, downlink and dual-link may not be realistic enough. The real beacon transmission scenario depends on the application. In this section, we study the performance of LTE regarding to real applications.

We choose intersection collision avoidance as the application for performance evaluation. The main reason is that LTE increases the communication coverage around intersections in urban environment while DSRC will likely not be able to provide the same coverage.

In general, the intersection collision avoidance service can be described as follows:

- 1) Given the GPS and the road map, a car approaching an intersection starts to broadcast beacons containing the status of the vehicle.
- 2) The car receiving the beacons transmitted from another car coming from the cross road gets aware of the existence of the car.
- 3) The car is going through the intersection. The other car stops before the intersection. Both cars keep sending beacons to notify their position to each other.
- 4) The car stops sending beacons after passing the intersection. The other car keeps sending beacons and starts to go through the intersection.
- 5) Both cars pass the intersection and stop broadcasting beacons.

In the scenario of intersection collision avoidance service, we assume that UEs are connected to the base station before sending beacons. Despite we do not consider random access in our simulations, it is worth to note that in reality random access may be used when a vehicle start to send a beacon when it approaches an intersection. This may incur extra delay for the initial beacon. However, this can be remedied by increasing the service range of the intersection collision avoidance service, allowing vehicles to transmit beacons as early as possible. Since we are focusing on preventing collision at intersections, the initial beacons are not as important as those sent when vehicles are close to intersections.

In our simulations, we set the intersection collision avoidance service range to 100 meters. As a vehicle is approaching an intersection (i.e., it is within 100 meter range), it starts to send beacons. Typically a vehicle should receive warnings 3 seconds before collision. This corresponds to 42 meters at 50 km/hour speed. We set the service range to 100 meter to guarantee the safety of drivers. The vehicle keeps broadcasting beacons as long as it is within the service range. Figure 6-4 illustrates the process of beacon transmission.

In this scenario, when a beacon is sent, the intended receivers are those who are in the same intersection area as the sender (i.e., within 100 meters to the same intersection as the sender). We count the number of intended receivers each time a beacon is transmitted for calculating the delivery rate.

In intersection scheme, the delivery rate is defined as the number of received beacons to the number of intended receivers, while the latter is defined as the number of vehicles within the same intersection area as the sender.

6.8 Simulation Settings and Results

We use VanetMobiSim [43] as our traffic generator. The scenario is a grid layout with intersections. Each road segment is 500 meters long. The base station is installed in the center of the road topology. Figure 6-5 shows the road layout. Each vehicle is placed randomly on the

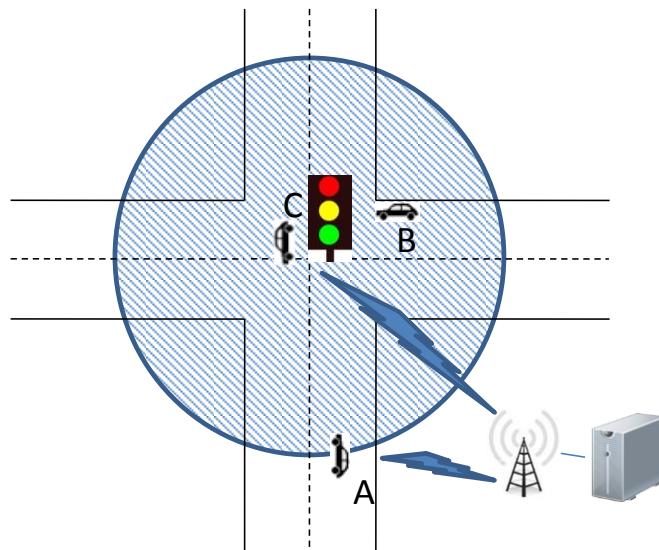


FIGURE 6-4 Vehicle a starts to send *beacons* to the base station when entering an intersection. Vehicle B and C keeps sending beacons because it is going through the intersection.

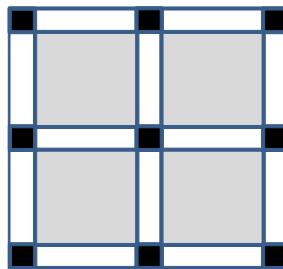


FIGURE 6-5 The road topology with intersections.

road map with initial speed 0 and then starts to move. The speed of each vehicle increases until it reaches the speed limit if there is no car ahead, otherwise it slows down to avoid bumping into the front car. There is no lane changing or passing allowed in our simulations.

TABLE 6-2 SIMULATION PARAMETERS FOR INTERSECTION SCENARIO

Simulation Parameters	Value
Simulated Area	1 km × 1 km
Service range	100 m
Layout	Grid layout, 9 intersections
Road Segment Length	500 meters
Road Structure	Two way/four

Simulation Parameters	Value
	lanes each way
Speed Limit	50 km/hour (13.9 m/s)
Packet size	100 bytes

As we can see in Figure 6-1 and Figure 6-2, the delivery rate and delay are between LTE uplink and dual-link. The threshold of LTE intersection is about 100 nodes, beyond which the performance drops quickly. The average delay is up to 0.3 s, while the maximum delay could be up to 1 s. This is not acceptable because generally the delay requirement of vehicular safety applications is assumed to be 100 ms. Considering the drivers' safety, we suggest 100 nodes should be the threshold below which LTE can support qualified performance for safety applications.

6.9 Conclusions and Discussions

In this chapter, we conduct simulations to evaluate the performance of LTE for beacon delivery. We focus on the capability of LTE regarding the delivery rate and delay. Multiple schemes are evaluated including 802.11p, LTE uplink, LTE downlink, and LTE dual-link. We also consider the real application scenario and evaluate the intersection scheme for LTE.

Due to the asymmetric capability of uplink and downlink, the uplink is the bottleneck for beacon transmissions. The delivery rate is very satisfactory when the number of nodes is

below a certain threshold. The delay of LTE schemes is much longer than DSRC, however, it is still a satisfactory result for safety applications when the number of nodes is below the threshold.

For intersection collision avoidance, our simulation study shows that the current stage of LTE should be adequate to support beacon transmissions for less than 100 nodes per base station to obtain satisfactory delivery rate and delay. Within this threshold, the delivery rate is almost 100% and the average delay is below 100 ms. The maximum delay is slightly higher than 100 ms but less than 200 ms. Beyond the threshold, the delivery rate and delay may not be good enough to ensure the drivers safety.

Our simulation is conducted using 5 MHz spectrum. Simply expand the bandwidth can support beacon traffic of more vehicles, however, due to the scarcity of spectrum, elegant approaches should be used to solve this problem. We point out the possible future research directions to researches of using LTE for VANET applications:

- 1) Broadcast may be applied for downlink transmissions to save the bandwidth consumption.

Some data aggregation algorithm may be applied to further reduce the download data amount.

- 2) Since vehicles are moving as platoons on the road, it is reasonable to cluster vehicles into groups based on the mobility status. As a result, beacons may be transmitted between cluster heads and thus further reduce the beacon traffic.

Chapter 7 A Cluster Based Architecture for Intersection Collision Avoidance Using Heterogeneous Networks

7.1 Introduction

There are several challenges regarding the usage of LTE for VANET safety applications. First, the support of intersection collision avoidance demands a large amount of data traffic between UEs and base stations, which is not likely to be accepted by network operators. In addition, extra traffic between UEs and base stations increases the effect of interference and thus decreases the delivery rate. The scheduler at the base station may also have difficulty to schedule transmissions within delay requirement, which is critical to intersection collision avoidance service.

To solve these problems, we propose a cluster based architecture for intersection collision avoidance service using both Wi-Fi and LTE technology. We choose Wi-Fi instead of DSRC because of its popularity and low cost, however, any short range communication technology can be applied to our architecture. When approaching an intersection, the Wi-Fi interfaces are used to transmit beacons to form a cluster. The vehicle closest to the intersection becomes the cluster head and maintains the status of the cluster. Only the cluster head is allowed to transmit/receive CAMs to/from base stations through LTE interfaces. Our cluster architecture allows CAMs to be transmitted efficiently without burdening the traffic load on base stations, improving the delivery rate and keeping the packet delay at a satisfactory level.

The rest of the chapter is organized as follows: in section 7.2, we briefly introduce the related clustering algorithms. We elaborate our architecture and clustering algorithm in detail in section 7.3. Simulations are described in section 7.4, followed by the conclusions.

7.2 Related Works

7.2.1 Clustering Algorithms

Many clustering algorithms have been proposed for routing and data dissemination purpose in VANETs [45]-[50]. These algorithms try to elect a cluster head who is responsible for transmitting data packets and organizing the cluster structure. The cluster heads or gateways can be used as forwarding nodes to propagate data. In this way, the data can be forwarded in an efficient way without incurring much routing overhead and overloading the channel.

In general, two approaches can be used for cluster creation and organization: 1) Passive clustering algorithm [45][46]: in this approach, data packets piggyback control messages for cluster creation and organization. It does not require explicit signaling or protocol specific messages for clustering purpose. The advantage is that the control overhead is significantly reduced. 2) Proactive clustering algorithm [47]-[50]: This approach is based on the regular transmission of HELLO messages by all nodes. The advantage is that the cluster can be created in a better way in terms of the cluster stability with the explicit control messages, but the protocol has to be carefully design to avoid overloading the channel when node density is high. Furthermore, both approaches can use additional information such as speed, mobility, and location to improve the cluster formation process. For example, in [51], the authors proposed a moving zone clustering algorithm that predicts speed and computes a similarity score. The similarity score is used to identify nodes with similar mobility patterns for cluster creation.

Using mobility information for cluster formation improves the stability of a cluster and thus generally achieves better performance.

7.2.2 Heterogeneous Architecture

In VANETs, due to the dynamic mobility pattern of VANETs, network connectivity can be intermittent. Heterogeneous mobile wireless broadband access architecture can be used to increase the coverage of wireless communications. In addition, load balancing can be applied between cellular network and VANETs. In [52], the authors proposed the MobTorrent framework which opportunistically makes use of vehicles' intermittent but high-capacity Wi-Fi contacts with roadside APs and other vehicles to improve the bandwidth available to them. The authors in [53] have addressed the issue of augmenting mobile 3G using Wi-Fi. The idea is to offload data on Wi-Fi whenever possible hence avoiding using the 3G link when Wi-Fi is available.

Integrated cellular network and VANETs can also facilitate the packet forwarding strategy. In [54], the authors propose a multi-network packet scheduling architecture to maximize the network throughput and keep latency and packet loss within the minimum requirements for vehicular network application classes. Different application classes are given different priority and mapped to different interfaces. The simulation shows better performance is achieved by using multi-network architecture.

7.3 Cluster Based Architecture

7.3.1 Assumptions

We assume each vehicle has both Wi-Fi and LTE interfaces installed or has mobile devices with these interfaces attached so that it can communicate to other vehicles through Wi-Fi and to base stations through LTE. Either the vehicle or the mobile device has GPS and a digital map providing location, speed and road information, etc. The road information such as the location of intersections is needed in our architecture so that the vehicle knows when it approaches an intersection.

We define the road segment to be the segment of road between two intersections. Each road segment/intersection is assigned an ID called road ID/intersection ID. This requires a minor modification to the digital map and it can be done during the construction of the map. For example, the TIGER map [14] record type 1 (RT1) and record type 2 (RT2) offered by U.S. Census Bureau can be used to construct a digital map. RT1 contains the information of a road, such as name, type, direction, start and end point. RT2 contains the information of the middle points of a road. Each road segment and intersection can be identified and given an ID during the construction of the map.

7.3.2 Architecture Overview

In general, the intersection collision avoidance service works as follows: when a vehicle approaches an intersection, it starts sending CAMs to vehicles on other roads indicating its existence. If the vehicle is equipped with Wi-Fi interface, CAMs can be transmitted by broadcasting. However, when node density is high, broadcasting could overload the channel. This is common in VANETs because the traffic is heavy during rush hour and the intersections

are usually the bottlenecks. If the vehicle is equipped with LTE interface, the CAMs can be transmitted to a base station and then be forwarded to vehicles on other roads. This causes problems also because the CAM transmissions put heavy burden on the base station considering the fact that CAMs are transmitted every 100 ms. Excessive connections increases the possibility of interference and packet error rate. It also increases the packet delay due to resource depletion.

In order to reduce the amount of traffic transmitted between User Equipments (UEs) and base stations, a clustering algorithm is needed. Many clustering algorithms have been proposed for routing or data dissemination purposes in VANET domains. These clustering algorithms may not be suitable for intersection collision avoidance service due to several reasons. First, to maintain the cluster structure, these algorithms usually requires successive control messages exchanges between cluster members and cluster heads, such as join messages and leave messages. This results in signaling overhead. Second, for intersection collision avoidance, the accuracy of the location of cluster members is very important. It is hard to keep the location information of each cluster members up to date. Since we are focusing on intersection collision avoidance service, a special clustering algorithm is needed for this purpose.

Due to these reasons, In this chapter we propose a light weight platoon-based intersection collision avoidance service using both LTE and Wi-Fi interfaces. The idea of our clustering algorithm is that, since vehicles are moving as platoons, it is reasonable to treat a platoon as a whole for intersection collision avoidance purpose. The vehicle closest to the intersection will be elected as the cluster head and is responsible for maintaining the cluster structure and transmitting/receiving CAMs to/from a base station. Vehicles on the same road that move in the same direction (toward or away from an intersection) will be in the same cluster. CAMs contains the start and end position of a platoon used for collision avoidance purpose. Our

architecture does not require explicit join and leave control messages, as long as cluster members are within the range of the platoon.

For intersection collision avoidance service, it is not necessary to maintain the cluster structure all the time. We define the cluster region to be the region in which vehicles send beacons for cluster formation. We define the intersection collision avoidance service region (abbreviate as *service region*) to be the region in which cluster heads send CAMs to base stations. The cluster region should be at least larger than or equal to the service region because we want the clusters to be built before the cluster heads send CAMs to base stations.

To avoid confusion, we refer beacons as the packets transmitted within clusters through Wi-Fi interfaces, and CAMs as the packets transmitted between cluster heads and base stations for intersection collision avoidance purpose. When a vehicle approaches an intersection, it first broadcasts beacons through Wi-Fi interface to form a cluster. After the cluster is built, the cluster head sends CAMs to the base station. The base station will forward CAMs to cluster

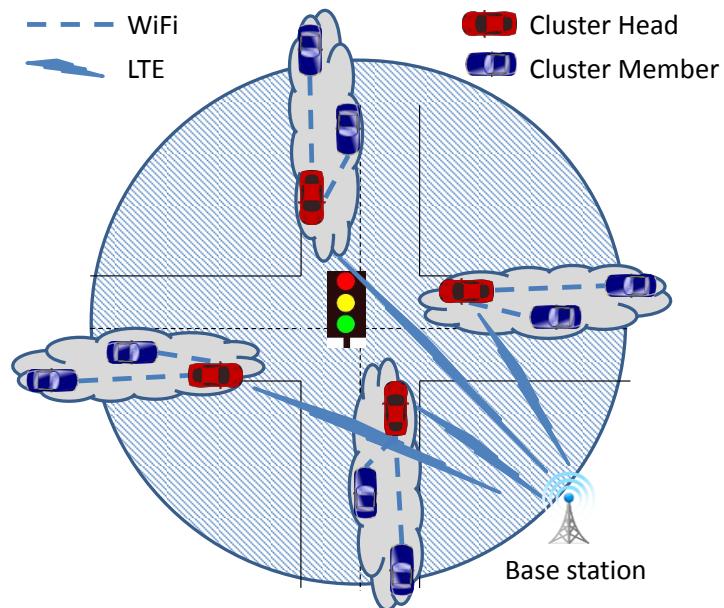


FIGURE 7-1 The clusters around an intersection.

heads on other roads. The cluster heads receiving the platoon information sent from the base station will broadcast it through Wi-Fi interface to their members. The cluster heads keep sending CAMs until the clusters pass the intersection. The cluster is dismissed then, meaning beacons and CAMs are no longer transmitted. In this way, our algorithm allows CAMs to be transmitted efficiently and significantly reduce the load of the base station. Figure 7-1 illustrates the cluster structure at an intersection.

7.3.3 Clustering Algorithm

7.3.3.1 Cluster Formation

The details of our clustering algorithm can be described as follows. Each vehicle can be either a cluster head or a cluster member. When entering into the cluster region, each vehicle is initialized as the cluster head. The cluster head broadcasts beacons containing its cluster range (with start and end position initially set to its location), the ID of road on which it is running,

Cluster Head ID	Road ID	Intersection ID	Last node ID	Start Position	End Position	Direction
32 bits	32 bits	32 bits	32 bits	128 bits	128 bits	1 bit

(A) THE FORMAT OF BEACON BROADCAST BY CLUSTER HEAD.

Cluster Head ID	Road ID	Direction	Start Position	End Position
32 bits	32 bits	1 bit	128 bits	128 bits

and the moving direction (Figure 7-2). It keeps broadcasting beacons until its state changes to cluster member due to the discovery of a closer cluster head, or the last member of the cluster passes the intersection. The latter requires the last cluster member sends an extra message when it passes the intersection. Other vehicles receive the beacons comparing its location to the cluster range. If the receiver is closer to the intersection and it is a cluster head, it stores the location information in its member table, updating the end position of its platoon if necessary, and keeps broadcasting beacons. The sender's state will be changed later when it receives the successive beacons broadcast by the new cluster head. If the receiver is a cluster member, it does nothing as it has been included in a cluster. Note that it may not be in the same cluster as the sender; however, it is not responsible for the correction of the sender's state. Only vehicles on the same road and moving in the same direction will process the beacon; otherwise the beacon will be discarded.

If the receiver's location is farther from the intersection than the sender and it is a cluster head, it changes its state to cluster member. After the cluster is built, the cluster member does not send beacons to the cluster head as long as it is within the cluster range. The only exception is the last cluster member, who will send back its location information to the cluster head after receiving the beacon. If the cluster head does not receive response from the last member, it will look up in its member table and broadcast beacons with the second last member ID, and the process repeats if no response is heard. Therefore, our clustering algorithm requires the cluster head and the last cluster member to exchange messages for cluster maintenance. If a cluster member does not receive beacons from its cluster head or any other cluster head closer to an intersection for a period of time, it sets its state to cluster head to form a new cluster. For example, a cluster member slows down to wait for red light will create a new cluster while its original cluster head passes the intersection. In this way, our clustering algorithm exchanges fewer messages to build and maintain a cluster.

7.3.3.2 CAM Delivery

The cluster head is responsible for transmitting CAMs to the base station. The CAM message includes the start location (the cluster head location) and the end location (the location of the farthest cluster member from the intersection) instead of transmitting location of every cluster members. After the base station receives the CAMs from the cluster heads, it stores the cluster information in its forwarding table, and forwards CAMs to cluster heads on other roads connecting to the same intersection. Each entry in the forwarding table contains the following information:

<Cluster Head ID, Road ID, Intersection ID, Start location, End location, timestamp>

The timestamp is used to remove the outdated entry a period of time after the base station stop receiving CAMs from the same vehicle. The cluster heads receive the CAMs from the base station and broadcasts to its cluster members so that they can be aware of the clusters on other roads and identify potential collisions.

7.3.3.3 Wi-Fi Channel Allocation Algorithm

In our architecture, vehicles broadcast beacons using Wi-Fi interfaces within clusters. In order to avoid interference between clusters on different roads, we design a Wi-Fi channel allocation algorithm. Our idea is to allocate channels as apart from each other as possible. With the aid of digital map, the channels can be allocated based on the road information. Given the road topology, the number of channel needed equals to the number of roads connecting to an intersection. The gap (in terms of channels) between each allocated channel can be calculated as follows:

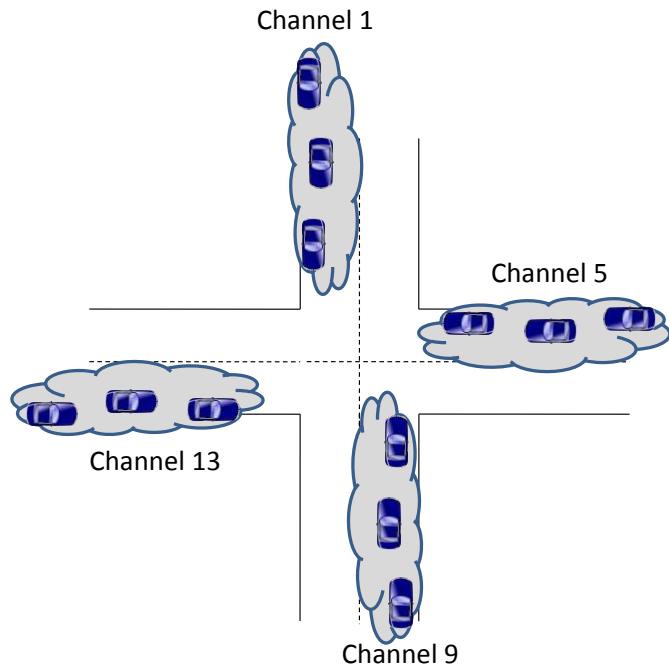


FIGURE 7-3 Different clusters use different channels.

$$\text{channel gap} = \frac{\text{total \# of channels}}{\# \text{ of roads} - 1} \quad (7-1)$$

where the total number of channels is the number of available channels in Wi-Fi frequency band (which is 13). Therefore, for a 3-leg intersection, the gap is $13/(3-1) = 6.5 \approx 6$, resulting in channel 1, 7, and 13 selected. Similarly, for a 4-leg intersection, the gap is $13/(4-1) \approx 4$ and channel 1, 5, 9, 13 are selected.

The next step is to allocate the channels in a specific order. It can be done by allocating channels to clusters in clockwise order starting from the cluster in the north of the intersection. For example, for a 4-leg intersection, the cluster in the north of the intersection will be allocated channel 1, followed by the cluster in the east allocated channel 5, followed by the cluster in the south allocated channel 9, and the cluster in the west will be allocated channel 13 (Figure 7-3). Since we assume each vehicle has GPS navigation system, each vehicle knows which channel it should use to communicate to other cluster members given the road topology information.

7.4 Performance Evaluation

In this section, we evaluate the performance of our protocol by simulations. We conduct our simulations with NS-3 (3.16) network simulator [41]. NS-3 has LTE module which implements most functionality defined in 3GPP specification. We created a grid road topology containing 25 intersections. Each road segment is 500 meter length. The base station is installed in the center of the road topology. A remote server is connected to PDN GateWay (PGW) for forwarding CAMs. We assume the server is connected to PGW using a dedicated line. Therefore, the delay between PGW and remote server is set to 0 in our simulations. Figure 7-4 shows the road topology.

We use VanetMobiSim [43] as our vehicle traffic generator. The scenario we created is intersections regulated by traffic lights. Initially each vehicle is placed randomly in the layout with speed 0. It starts moving and increases its speed until it reaches speed limit or approaches a car ahead of it. Considering the speed limit is 50 km/hour, and typically a car is warned 3 seconds before collision, this results in about 42 meters before arriving at the intersection center. In our simulations, we set the radius of the service region to 70 m for safety reasons, within which vehicles sends CAMs to base station. The radius of the cluster region is set to 100 m within which vehicles send beacon to create clusters. The parameters are listed in Table 1, 2, and 3.

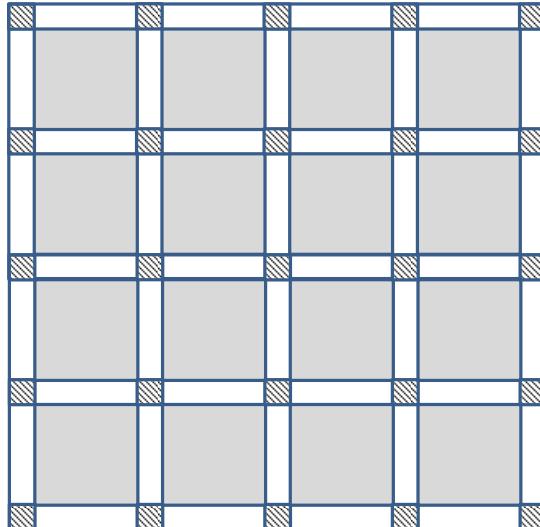


FIGURE 7-4 The road topology.

TABLE 7-1 SIMULATION PARAMETERS

Parameter	Value
Simulated Area	2 km × 2 km
Layout	Grid layout, 25 intersections
Service Region	70 m
Cluster Region	100 m
Road Segment Length	500 meters
Road Structure	Two way two lanes
Speed Limit	50 km/hour
Simulation Time	60 seconds
Beacon Transmission Interval	100 ms
CAM Transmission Interval	100 ms

TABLE 7-2 WI-FI SETTINGS

Parameter	Value
Protocol	802.11b
Tx Power	16 dBm
Date Rate	11 Mbps
Transmission Range	100 meters
Tx Gain	1 db
Rx Gain	1 db
Propagation Delay Model	Constant Speed Propagation Delay Model

TABLE 7-3 LTE SETTINGS

Parameter	Value
Base Station Tx Power	40 dBm
UE Tx Power	20 dBm
Bandwidth	5 MHz (25 RBs)
Scheduling Algorithm	Proportional Fair
Simulation Time	60 seconds

We compare the performance of three schemes:

- Wi-Fi Only: each vehicle has only one Wi-Fi. CAMs are broadcast through Wi-Fi.
- LTE Only: each vehicle has only one LTE interface. CAMs are transmitted through LTE interfaces and forwarded by the base station.
- Heterogeneous: both Wi-Fi and LTE are used. Wi-Fi is used for cluster construction and maintenance. LTE is used for CAM transmission.

We use two metrics to evaluate the performance:

- Delivery rate: For collision avoidance service, an important goal is to reliably deliver the CAMs to the target vehicles. In Wi-Fi Only and LTE Only schemes, the target vehicles should be all vehicles on roads other than that of the sender. In Heterogeneous scheme, the target vehicles are the cluster heads on other roads. Therefore, we define the delivery

rate as the ratio of the total number of received CAMs to the total number of expected recipients. The expected number of recipients is calculated by counting the number of vehicles or cluster heads on other roads each time when a CAM is sent.

- Packet delay: the delay from the time the CAM is created to the time the CAM is received by a vehicle either directly by broadcast or indirectly by forwarding via the base station.

As we can see in Figure 7-5, the delivery rate decreases as the number of nodes grows. For Wi-Fi Only scheme, this indicates the channel has been saturated and collisions happen frequently. For the other two schemes, this is due to the fact that the transmission of CAMs introduces too much interference as the number of the nodes grows. Most of the CAMs cannot be successfully received by the base station and the target receivers. In most cases the delivery rate of the other two schemes are comparable, while that of the Heterogeneous is much higher. Additionally we can see the total number of CAMs transmitted in Figure 7-6. In Wi-Fi Only and LTE Only schemes, the total number of CAMs transmitted increases linearly as the number of nodes grows, while that of Heterogeneous scheme just increases slightly due to the usage of the clustering algorithm. The number of generated CAMs is in proportional to the number of clusters created. Figure 7-5 and Figure 7-6 show that our clustering algorithm effectively reduces the number of CAM transmissions and thus achieves much better delivery rate.

As for the delay, we can see in Figure 7-7 that the delay of Wi-Fi Only is much less than the other two schemes. This is not surprising because the direct transmission between two Wi-Fi nodes introduces much less delay factors. In LTE Only and Heterogeneous schemes, the CAMs have to go through the following process to be received by the intended receivers:

- 1) CAMs are transmitted to the base station from the senders.
- 2) CAMs are received by the base station as the order scheduled by the scheduler.

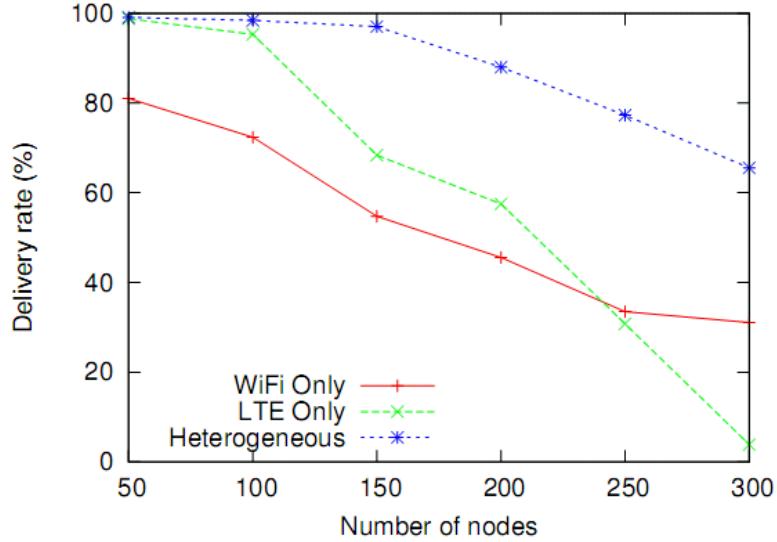


FIGURE 7-5 Delivery rate.

3) CAMs go up the LTE protocol stack MAC/RLC/PDCP.

4) The server application decides to whom to forward the CAMs.

5) CAMs go down the LTE protocol stack.

6) CAMs are scheduled for transmission.

7) CAMs are received by the target vehicles.

Although the delay of LTE Only and Heterogeneous is much longer than Wi-Fi Only scheme, it is around 100 ms which is acceptable for our application. The delay is slightly reduced when the clustering algorithm is applied. In our simulations, the delay increases slightly when node density grows because the radio resource is not sufficient to schedule the transmission in time. A special scheduling algorithm may be needed to solve this problem.

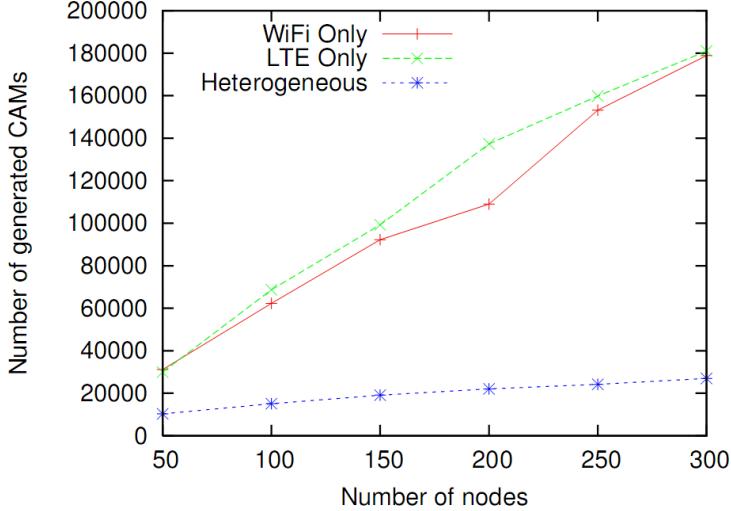


FIGURE 7-6 Total number of generated cams.

7.5 Conclusions

In this chapter, we propose a clustering architecture for intersection collision avoidance using Wi-Fi and LTE. Wi-Fi channels are used for in-cluster communication and LTE channels are used for transmitting CAMs. Our novel clustering algorithm is specifically designed for intersection collision avoidance service. It only requires signaling between the cluster head and the last cluster member for cluster creation and maintenance. Moreover, we propose a channel allocation algorithm to use different Wi-Fi channels for different clusters to avoid interference. The simulations show our architecture performs much better than other schemes in terms of the delivery rate.

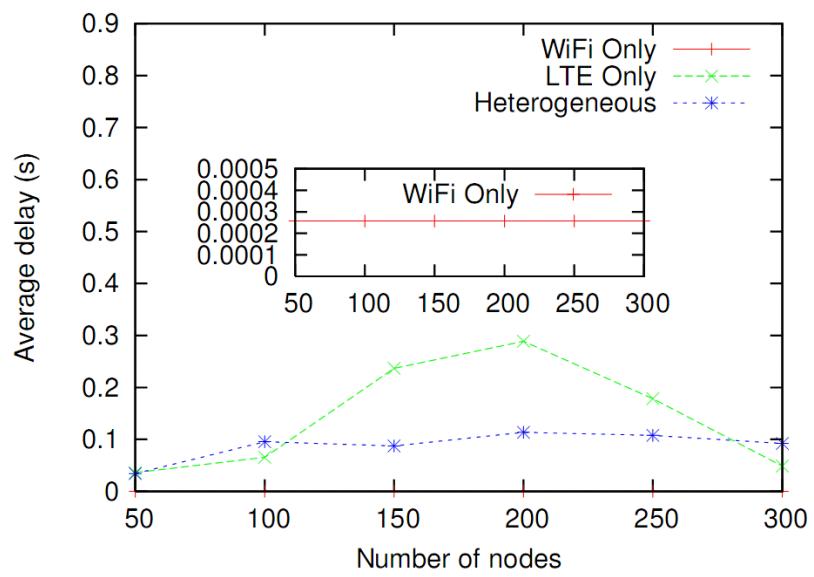


FIGURE 7-7 Average packet delay.

Chapter 8 Priority-Based Congestion Control

Algorithm for Cross-Traffic Assistance on LTE Networks

8.1 Introduction

For cross-traffic assistance, the base station applies appropriate algorithm to identify potential collision patterns and sends warning messages to vehicles in danger. Because LTE offers good communication around intersections, so it is a potential alternative for cross-traffic assistance service, but it is not clear if it can support the traffic of beacon transmissions given the fact that radio resource is scarce today.

The amount of traffic generated for beacon delivery can be determined by a number of factors: the cell size, the number of intersections per cell, the number of vehicles per intersection per cell, and the transmission interval. The cell size in LTE can be up to tens of kilometers, but in practice, because small cell size facilitates frequency reuse and therefore improves capacity, the cell size is usually between 1 km to 5 km. Assuming a typical cell size of 1 km is used, and 50 intersections per cell, 10 vehicles per intersection, 5,000 beacons are generated per second if each vehicle transmits beacons at 10 Hz. This generates considerable amount of traffic in the uplink. Normally the beacon transmission interval can range from 100 ms to 1 s. In general, 100 ms is usually assumed to guarantee the safety of drivers. If adaptive beaconing is used, the number of beacons generated can be reduced.

For use by the US public safety community, Federal Communications Commission (FCC) assigned 700 MHz Public Safety Band (763-768/793-798 MHz) for broadband communications

[44]. Note that this is the band shared by all public safety services. Currently there is no standard of the bandwidth allocation for each safety services. It is unclear how much bandwidth will be used for vehicular safety services, and furthermore, how much will be used for cross-traffic assistance application. It is critical for safety applications to serve users in urgent situation; for example, the users who are driving through an intersection are the ones who need cross-traffic assistance service most. In case the traffic load of beacon transmissions reaches the bandwidth limit, only a subset of users can be served. These users should be served based on the priority indicating the urgency they need the service.

In this chapter, we discuss the applicability to prioritize users for cross-traffic assistance in order to fit the bandwidth requirement, while satisfying the application needs. We assume that there is a pre-defined bandwidth threshold (e.g., 1 MHz) assigned to cross-traffic assistance, indicating the available resources it can manage. It is up to future researches to decide how much bandwidth should be assigned to this application. The threshold may be dynamically adjusted to the network load. The advantage of this approach is the flexibility of resource management: available resources can be assigned to applications dynamically, as long as the total bandwidth usage does not exceed the limit. The dynamic threshold adjustment is out of the scope of this dissertation. In this chapter, we propose a priority-based congestion control algorithm specifically for cross-traffic assistance. In our scheme, each user is given a priority based on certain criteria. In case the bandwidth threshold is reached, low priority users will be removed to reduce the cell load. The users who are crossing intersections will get cross-traffic assistance and thus the service requirement is satisfied. Not so much literature discussing about the load control of vehicular safety applications on LTE networks so far. We expect more researches can be done in this area to improve the safety and driving experience using LTE.

8.2 Related Works

The capability of LTE to support vehicular safety applications is an important issue. Generally speaking, two approaches can be used for cell load management: admission control and congestion control. Admission control is used to block user connections when the cell load reaches the limit. On the contrary, the congestion control is used to gracefully reduce the cell load either by sacrificing the quality of connections or by removing existing bearers.

There are several mechanisms proposed for LTE admission control and congestion control. In [58], a predication radio admission control is proposed. The mechanism not only takes into account the frequency resource utilization but also the throughput. It provides the flexibility to the operators for managing cell load and user performance.

In [57], the authors propose a pre-emption congestion control algorithm. The pre-emption algorithm allows high priority requesting bearers to displace low priority connected bearers in order to reduce cell load. The algorithm coupled with a priority-based admission control can achieve low dropping and blocking probabilities.

8.3 System Architecture

8.3.1 Scenario

We assume each UE has GPS and digital map so that it knows when it approaches an intersection. The beacon transmission from a UE to a base station may consume considerable energy, so we assume UEs can get plenty of power from vehicles. When a UE approaches an intersection, it tries to connect to a base station for cross-traffic assistance service by sending scheduling request via random access for initial connection setup. We define the “service region”

to be the bounding box centered at an intersection, within which vehicles sends beacons to the base station. Considering the speed limit is 50 km/hour, and typically a car is warned 3 seconds before collision, this results in the distance about 42 meters before collision. The service region should be larger than this to provide quality service for drivers. Nonetheless, the basic requirement of cross-traffic assistance service is the drivers who are crossing an intersection should be served.

When the base station receives the request, it schedules resource blocks for beacon transmissions. After that, beacons are transmitted every 100 ms until the UE moves out of the intersection. Vehicles will not send beacons outside of the service region. Another similar scenario is intersections managed by stop signs, where vehicles stop at intersections first and take turns to cross.

8.3.2 Architecture Overview

The system architecture consists of three parts: resource scheduling, congestion control and state information management (Figure 1). The resource scheduling module is accountable for allocating resources and running scheduling algorithm. The congestion control module prioritizes users based on certain criteria. It interacts with resource scheduling module to retrieve the cell load condition and informs it to release resource if necessary. The state information management stores information such as the current cell load, the load contribution, the priority of each user, etc.

When there is a new connection request, the resource scheduler allocates available RBs (Resource Blocks) in the resource grid for it. After resources have been allocated, it determines if the current load reaches the limit threshold. If so, the resource scheduler sends load reduction request to the congestion control module, where the priority-based congestion

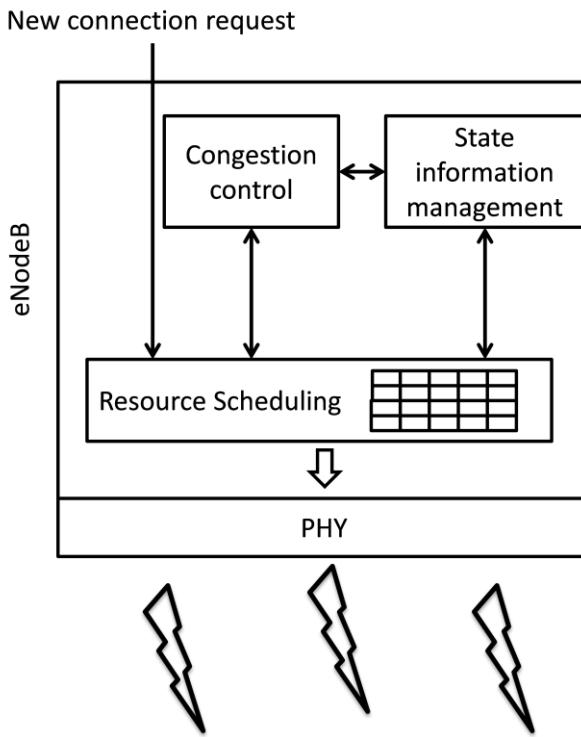


FIGURE 8-1 The system architecture

control algorithm will be activated to reduce the system load. We will discuss the detail of each part in the following sections.

8.3.3 LTE Resource Management

LTE uses OFDMA (Orthogonal Frequency-Division Multiple Access) as the multiple access technology. Multiple access is achieved by assigning subcarriers to individual users. In LTE, the total bandwidth is divided into Resource Blocks (RBs) in the frequency domain. Each RB contains 12 subcarriers and each subcarrier is 15 kHz. In time domain, LTE defines 10 ms frame which is further divided into 1 ms subframe. Each subframe contains two slots in 0.5 ms length. Each RB corresponds to one slot in time domain. Data are transmitted in units known as

Transport Blocks (TB), each of which is passed down per Transmission Time Interval (TTI), where a TTI is 1 ms, corresponding to one subframe duration. TB corresponds to Media Access Control (MAC) Protocol Data Unit (PDU); it is the minimum unit for scheduling.

When receiving new connection request, the resource scheduler has to allocate RBs for it. Because of the repeating resource allocation and release, a bunch of continuous vacant RBs (called spaces) in time and frequency domain appears in the resource grid. The first task is to find spaces big enough for the new request. Different strategies can be used to find available spaces [56]. The two common approaches are:

8.3.3.1 First fit

Find the first space that can fit the TB. If there are not enough RBs in the current TTI, try to find resources in the next TTI. This strategy minimizes the response latency, and thus is useful for delay sensitive traffic.

8.3.3.2 Best fit

This strategy tries to find the space that is just large enough to accommodate the TB. It helps to reduce the fragmentation in the resource grid.

We use the first fit strategy to find available RBs because the beacons are delay sensitive: every 100 ms a UE sends a beacon to its base station. A beacon is regarded as outdated 100 ms after it has been generated and will be discarded. When receiving scheduling request, the resource scheduling algorithm tries to schedule resource in 100 ms window, from TTI_{cur} to $TTI_{cur} + 100$, where TTI_{cur} indicating the current TTI. If the resource allocation succeeds, the beacons will be transmitted periodically every 100 ms. If there is no available resources, i.e., the cell load reaches the limit, we assume there are reserved resources which can be used to accommodate the new request, and at the same time the congestion control algorithm will be activated. Figure 8-2 illustrates the resource scheduling algorithm.

8.4 Cell Load management

In wireless radio networks, the base station should allow access of as many users as possible to increase revenue. On the other hand, the quality of service should be guaranteed in order to provide satisfactory service. The maximum number of users a base station can support is bound by the system bandwidth. Under the restriction of QoS, if the maximum bandwidth is achieved, new connection requests should be rejected. The cell load can be expressed as follows [57][58]:

$$L = \sum_i L_i \quad (8-1)$$

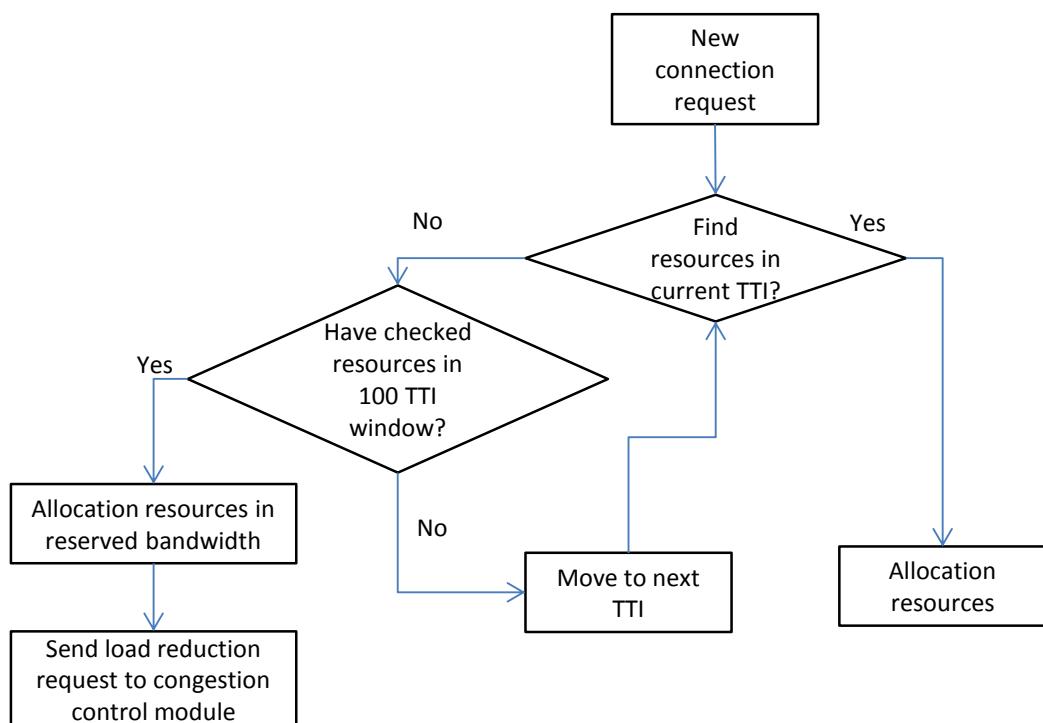


FIGURE 8-2 resource scheduling algorithm

where L is the cell load, L_i is the load of each bearer i .

Generally speaking, there are two ways to control the cell load:

8.4.1 Admission control

Admission control is used to determine if a new connection request should be accepted based on some criteria. It could be non-preemptive or preemptive. In non-preemptive admission control, a new connection can be satisfied as long as the load request does not exceed the bandwidth limit.

Preemptive admission control can be used when the addition of the estimated load of new bearer reaches the bandwidth limit and its priority is higher than that of any connected bearer. In this case, lower priority bears will be displaced by the new bearer until the following condition satisfied:

$$\sum_i f(L_{new}, L_j) L_j + L_{new} \leq L \quad (8-2)$$

$f(L_{new}, L_j)$ is a function such that if bearer j has lower priority than the new bearer, $f(L_{new}, L_j) = 1$, otherwise, $f(L_{new}, L_j) = 0$. The existing bearers should be sorted based on the priority and be replaced from the lowest priority bearer first until Eq (8-2) is satisfied.

8.4.2 Congestion Control

Congestion control is used in order to reduce the load to an acceptable level when cell overload is detected, for example if the cell load remains above a threshold for some period

subframes. If congestion is detected the system must remove a subset of the connected bearers until the load is reduced to an acceptable level.

Similar to admission control, congestion control can be categorized as non-preemptive and preemptive. Eq (8-2) can also be used for load reduction. The main difference between admission control and congestion control is the timing they are applied: admission control is activated before the new request has been accepted, while the congestion control is activated after the new request has been accepted. In admission control, the load of the new request may not be known at the time the request received, and thus the estimated load is used instead of actual load. This may result in the unnecessary removal of low priority bearers. In congestion control, the new request will be accepted before congestion control is activated, leading to the possibility of temporarily exceeding the load threshold. In LTE the MAC scheduler should be able to cope with a short period of overloading with graceful performance degradation. In a word, admission control is an active load control mechanism as opposed to passive for congestion control.

8.5 Priority-Based Congestion Control Algorithm

In this chapter, we propose a priority-based congestion control algorithm for cross-traffic assistance service. The reason we choose congestion control over admission control is that, the information of the status of vehicles may not be known before the new request is accepted, and thus using admission control may mistakenly reject high priority users. To accurately keep high priority users is important for safety applications, so the congestion control is used in our design.

As mentioned earlier, using congestion control could leads to temporary cell overloading. Even though the MAC scheduler could absorb the overload traffic for a short time, this could

lead to increasing bit error rate and incur more retransmissions. It may not be acceptable for beacon transmissions because of the emergency information it conveys, therefore In this chapter, we assume there is a “buffer” (i.e., reserved resource blocks) to accommodate the temporary overload.

When the congestion control module receives load reduction request from resource scheduling module, it calculates priority by sorting all users based on certain criterion. For cross-traffic assistance, we propose two methods for prioritization:

8.5.1 Prioritization by distance to an intersection

Because the vehicles near an intersection are the ones that need collision warning service most, the priority of each user is calculated based on the distance of the vehicle to the intersection. The closer the vehicle is, the higher the priority.

8.5.2 Prioritization by arrival time to an intersection

Calculating priority based on distance to an intersection may not be accurate. For example, a vehicle drives at high speed will approach an intersection more quickly than the one drives at low speed. Another way for prioritization is to calculate priority based on arrival time to an intersection. It can be calculated easily given the speed of the vehicle and the distance to the intersection. The short the time is, the higher the priority. One special case is when vehicles stop at intersections waiting to cross. We give the highest priority to these vehicles in this situation.

To check if the current load reaches the limit, we define the load contribution L_i of each user i as follows:

$$L_i = \frac{R_i}{R_{total} \cdot \Delta T} \quad (8-3)$$

Where R_i is the number of allocated RBs, R_{total} is the number of total RBs in system bandwidth, and ΔT is the inter-arrival time of beacons. The total load is:

$$L = \sum_i L_i \quad (8-4)$$

If the total load reaches the limit, i.e., $L \geq 1$, the low priority user i needs to be removed in order to reduce the load.

$$\sum_i L_i \geq \Delta L = 1 - L \quad (8-5)$$

The bearers are removed starting from the one with lowest priority until Eq (8-5) is satisfied. After that, it keeps monitoring the load for a period of time until it drops below the threshold, otherwise it runs the load reduction process again. The disconnected UEs may use random access to regain service when it is approaching the intersection and obtaining high priority. Figure 8-3 shows the congestion control algorithm.

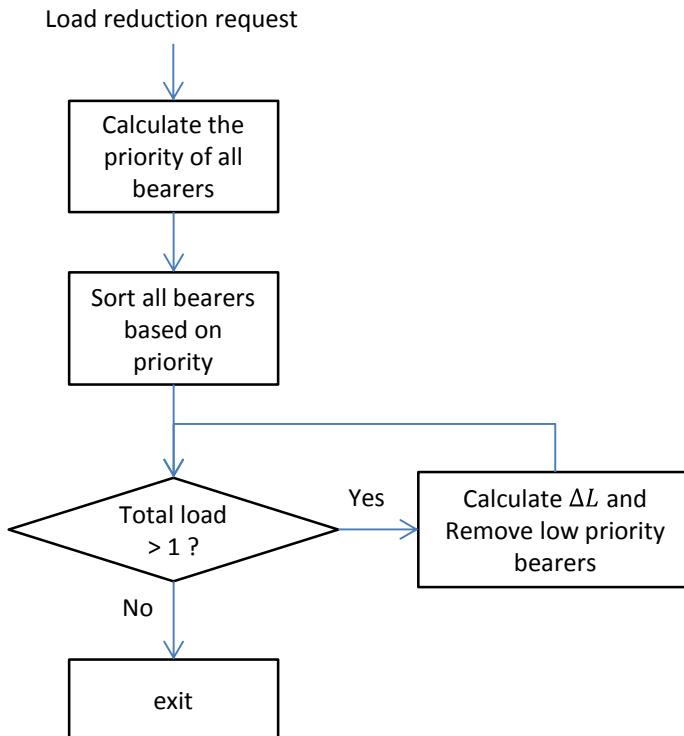


FIGURE 8-3 Congestion control algorithm

8.6 Performance Evaluation

In this section, we evaluate the performance of congestion control by simulations. We conduct our simulations with NS-3 network simulator with LTE-EPC extension. We created a grid road topology with 25 intersections. Each road segment is of 500 meter length. The base station is installed in the center of the road topology, and every UE is connected to the base station. Due to the lack of random access in current NS-3 LTE implementation, we simply ignore the beacons sent from low priority UEs instead of disconnecting them when bandwidth limit is reached, until them regain high priority. We understand that with this limitation the evaluation may not be realistic enough compared to the real environment, however, it should give us a sense of how the prioritization scheme could help manage the bandwidth utilization.

For the configuration of LTE, we use the standard settings in LTE module of NS-3 which provides about 5 km communication range. We set the service region to be 140 m by 140 m centered at each intersection. This is equivalent to 5 seconds before reaching the intersection center at speed 50 km/hour.

We use VanetMobiSim as our vehicle traffic generator. The scenario we created is intersections regulated by traffic lights. Initially vehicles are placed randomly in the layout with speed 0. They start moving and increase speed until reaching speed limit or approaching other cars ahead. The simulation starts at 10s to skip the initial vehicle movement. The simulation parameters are listed in Table 8-1.

TABLE 8-1 SIMULATION PARAMETERS

Parameter	Value
Simulated area	1km × 1km
Layout	Grid layout, 25 intersections
Service region	140 m × 140 m
Road segment length	500 meters
Road structure	Two way × two lanes
Speed limit	50 km/hour
TTI	1 ms
eNodeB Tx	30 dBm

Parameter	Value
power	
Bandwidth limit	1 MHz (6 RBs)
Simulation time	60 seconds
Beacon transmission interval	100 ms

We compare the performance of the following methods: the non-priority mode, the prioritization by distance to an intersection, and the prioritization by arrival time to an intersection. In non-priority mode the base station accepts beacons when receiving scheduling request without running congestion control algorithm. To see if our schemes can serve vehicles close to intersections, we calculate the average distance to an intersection center. The average distance is calculated based on the location information in beacons that the base station receives. As we can see from Figure 8-4, the average distance to an intersection is shorter for the prioritization based on the distance to an intersection. It is because without prioritization, the base station simply accepts beacons on the first come first serve basis. It is not guaranteed that the UEs closer to intersections will be served first. Similarly, the average arrival time to an intersection has been calculated and shown in Figure 8-5.

Another metric we use is the drop ratio. The drop ratio is defined as the number of the rejected beacons to the number of the accepted beacons. For non-prioritization scheme, the beacons are rejected due to the cell overload. New arrival beacons can only be accepted after

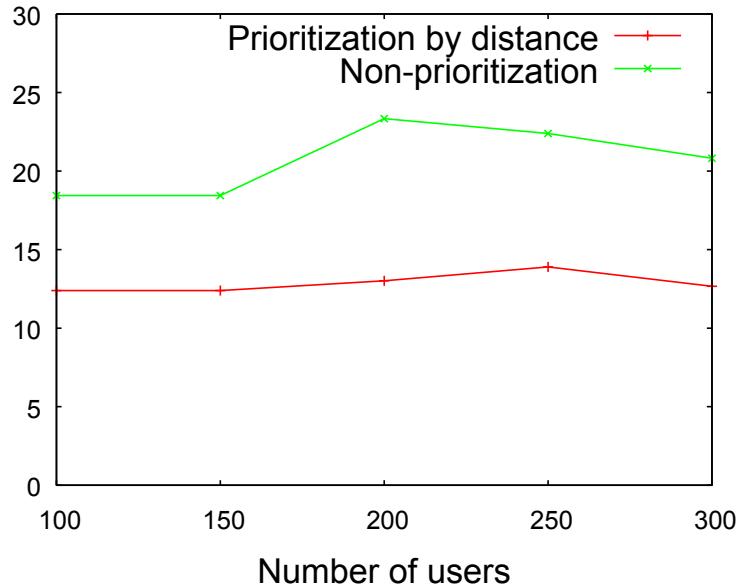


FIGURE 8-4 The average distance to an intersection.

some users move out the service region, resulting in load reduction. For prioritization scheme, the rejected beacons are the ones that are removed by the congestion control algorithm. As shown in Figure 8-6, the drop ratio of both prioritization schemes is smaller than non-prioritization scheme. This is because with prioritization scheme, beacons can be accepted if it has higher priority than any of existing bearers. From the drop ratio we can see if every beacon can get the opportunity of acceptance as oppose to being blindly rejected.

One thing that is not trivial in our simulations is that, it is not clear which prioritization scheme servers better. We think different scheme can be applied in different scenarios, for example, prioritization based on arrival time can be applied to the scenario where intersections are regulated by stop signs, because the driver who arrives an intersection takes precedence of crossing. More studies should be done for this issue.

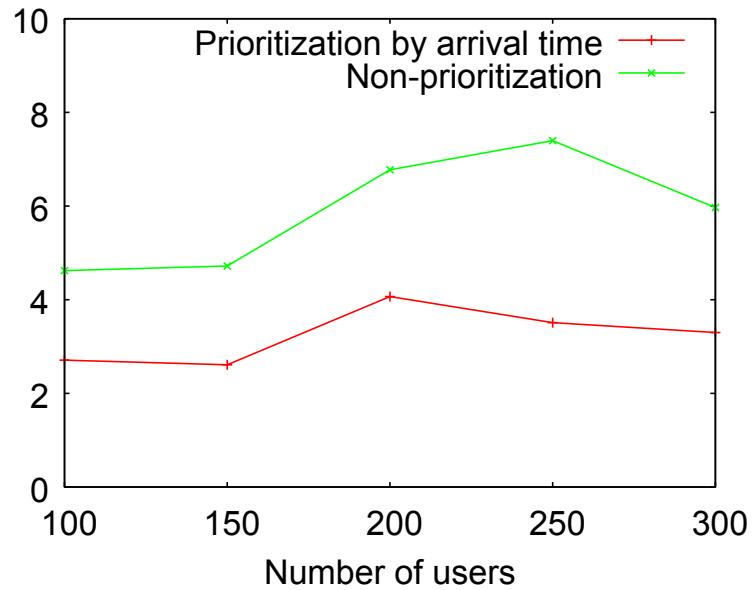


FIGURE 8-5 The average arrival time to an intersection.

8.7 Conclusions and Future Works

In this chapter, we proposed a priority-based congestion control algorithm for cross-traffic assistance using LTE networks. We first define the service region within which the cross-traffic assistance should offer service. The priority is assigned based on the distance to an intersection or the arrival time to an intersection. The simulations show our methods can effectively control the cell load while provide service based on the urgency of users.

We consider the cross-traffic assistance service in this chapter. For different vehicular safety applications, different criteria may be used for prioritization. For example, beacons sent by vehicles moving at high speed may be given higher priority than those sent when vehicles are at low speed on highways. Or, beacons sent by vehicles taking lane changes should be given precedence over others. We think every safety application should have a priority scheme due to the limited bandwidth and for the flexibility of load management. Furthermore, priority can also

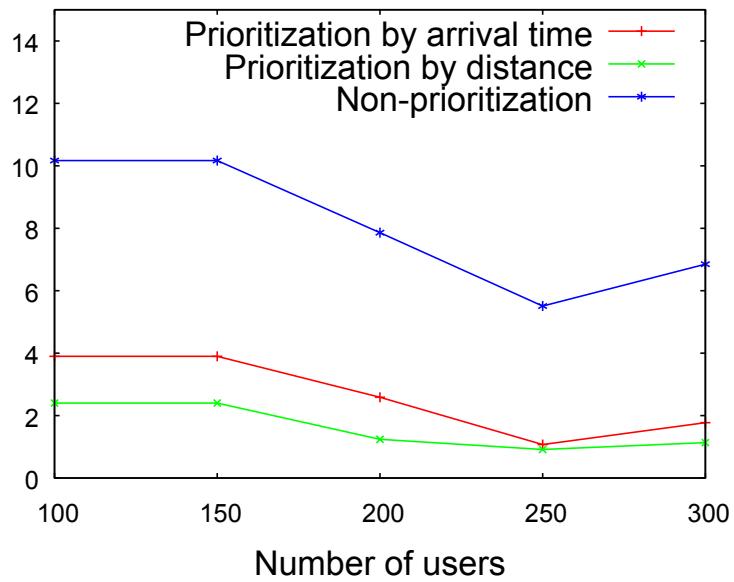


FIGURE 8-6 The drop ratio.

be given to different services, allowing the prioritization among services. More researches should be done to understand the validity of this priority approach. We leave this as the future work.

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