EFFICIENT SAFETY MESSAGE DISSEMINATION METHODS IN VEHICULAR ADHOC NETWORKS

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EFFICIENT SAFETY MESSAGE DISSEMINATION METHODS IN VEHICULAR ADHOC NETWORKS

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CHAPTER 1

INTRODUCTION

Vehicular ad-hoc networks (VANETs) are networks in which vehicles are connected by wireless communication. This communication between vehicles enables drivers or vehicles to receive more information than ever before.

VANETs have been an important component in the connected vehicle project [1], which has been driven by the U.S Department of Transportation in an effort to improve driver safety and help people drive vehicles more easily. The connected vehicle project has become a promising solution to intelligent transportation system. As a result, many car makers are beginning to develop the connected vehicles. The development and test of connected vehicles requires many testbeds in multiple locations. In Michigan [2], about 9,000 vehicles are on roads for the testing of the project. Another important application in the connected vehicle project will be the self-driving car which is a vehicle that can drive itself without any intervention from human drivers (for example, Google Self-Driving Car [3]). As the self-driving cars start appearing on roads, the network between these self-driving cars will be an essential part of driving. These cars will get more information from other vehicles and drive more safely by themselves. This is the technology can be available in the near future.

In the connected vehicle, the communication between vehicles is a key technology. Beside the communication, another important factor is sensing technology. Many high-end vehicles are already equipped with a lot of sensors. These sensors can collect data that is critical to driver safety and can be used to prevent possible traffic accidents. However, this sensing technology cannot solely support driver safety without wireless communication between vehicles. There are situations that the sensing technology cannot work as expected due to environmental issues such as severe weather or strong light reflection. Moreover, the fundamental weakness of the sensing technology is the limitation of sensing coverage.

Usually, a single sensor can cover several hundred meters. However, if some obstacles or vehicles are near to the vehicle and block the sensors, the sensors cannot sense other vehicles beyond the obstacles. If information can be shared between vehicles, the coverage of a sensor can be extended beyond its physical limitation.

With the communication, vehicles can send and share information with neighboring vehicles. This information sharing enables vehicles to recognize the environment beyond its sensing coverage. Also this wireless packet includes more important information than a single sensor can such as position, direction, speed or even the size of vehicle.

The communication can be extended to connect vehicles not only with their neighboring vehicles but also with another network. The safety information can be delivered up to several miles through multi-hop communication. In multi-hop communication, vehicles forward the information to other vehicles that have not received the information. Then, vehicles can obtain the details of accidents from several miles away. In addition, this multi-hop communication enables vehicles to access the Internet and cloud services. There are devices at road sides, which are connected to the Internet. When a vehicle is far from an access point, the multi-hop forwarding through other vehicles allows a vehicle to receive or send messages from and to the access point. Then, a vehicle can access the Internet without the need for any other devices.

To accomplish these applications through the use of VANETs, developing efficient methods for the dissemination of information between vehicles is critical. There are several factors that pose challenges such as congestion of a channel, high or low vehicle-density, high-speed moving of vehicles, short intervals for vehicles to communicate, unstable wireless channels or complicated standards.

Considering those factors, two cases are studied in this thesis. The first case highlights sending a large amount of information to a road side unit that is located far from the source of information. The second case demonstrates broadcasting information at intersections to each direction. In the first case, multimedia information is a good example of a large amount of data that would be transmitted. Multimedia information is very useful to investigate car accidents from a remote control center. To send a large amount of information, it is required to have enough bandwidth. Using multiple channels in VANETs is an efficient way to accomplish this requirement. However, using multiple channels presents a challenge with low density in each channel. To solve this problem, a network coding based-method is suggested in this proposal. The second case demonstrates the broadcasts of information at intersections. To send information in each direction at intersections, it would require several packet transmissions. However, these several transmissions bring extra delay. Another problem is packet collisions caused by simultaneous packet transmissions. To reduce the delay as well as the collisions, a medium access control (MAC) layer protocol is introduced in this study. This method can control the order of packet transmissions, which reduces the delay and avoids the collisions.

This thesis proceeds as follows: chapter II describes background and related literature survey. Chapter III, IV and V explain proposed methods. Chapter VI describes conclusions and future research.

CHAPTER 2

BACKGROUND AND RELATED RESEARCH

2.1 Vehicular Networks

Every year there are many victims from car accidents on roads. Besides the number of fatalities, the emotional toll and financial cost related to the accidents is huge. The estimated number of fatalities from traffic accidents in 2012 is nearly 34,000 [4]. The financial cost from these crash deaths was estimated at $41 billion including medical and work loss costs [5]. In an effort to reduce these car accidents and related costs, the Federal Communication Commission (FCC) assigned 75 MHz bandwidth at 5.9GHz for the purpose of vehicular networks [6]. This bandwidth can be used for vehicle-to-vehicle and vehicle-to-infrastructure communication. While the main purpose of this bandwidth is for safety, it also can support various types of other traffic. This bandwidth is free to use, but all vehicles should follow the rules of operation according to standards since this bandwidth is closely related to public safety.

The operation of communication devices in VANETs is specified mainly by two standard bodies: IEEE 1609 [7, 8, 9, 10, 11] and IEEE 802.11p [12]. While the IEEE 802.11 specifies the low-layer operation such as medium access control (MAC) and physical layer (PHY), the IEEE 1609 standard describes the upper-layer operation including network, security and application area. The IEEE 1609 standard consists of four parts. The IEEE 1609.1 standard describes the resource management for applications to efficiently use given resources. The IEEE 1609.2 standard describes the security area. The IEEE 1609.3 standard describes the network and transport area services. The IEEE 1609.4 standard describes the methods to support multi-channel operation. The IEEE 802.11p is an approved amendment to the IEEE 802.11 standard. Since the IEEE 802.11 standard usually supports the communication between fixed nodes, the IEEE 802.11p standard enhances the IEEE 802.11 standard to support the communication between high-speed moving vehicles and road-side infrastructures. The IEEE 1609.4 and IEEE 802.11p standards define the operation of vehicles in the domain of frequency spectrum and timing intervals. For the frequency spectrum that the FCC announced, there are seven channels. Each channel has 10 MHz bandwidth. One channel, assigned for safety purpose only, is called the control channel (CCH). The other six channels, called service channels (SCHs), can be used for safety and non-safety applications. Besides these channels, there are intervals to define operation in time domain. A basic interval is known as a synchronization (SYNC) interval which includes a control channel interval (CCHI) and a service channel interval (SCHI). The duration of synchronization interval is 100 msec. Vehicles are supposed to have a global positioning system (GPS) device and can synchronize with an error of significantly below 1 usec at the beginning of each SYNC interval. The duration of the control channel interval and the service channel interval is 50 msec at default, respectively. During the control channel interval, vehicles must stay only on the control channel. During the service channel interval, vehicles can select one of available service channels. This operation is shown in Figure 1.

The VANETs standards are based on a transceiver that can operate only on a single channel. With this device, vehicles cannot receive messages on the control channel while they are on other service channels. So, all vehicles must stay on the single control channel during the control channel intervals to receive safety messages from all the neighboring vehicles.

This channel structure results in inefficient bandwidth usage. Since only one channel is used during the control channel interval, only about 1/7th of the total bandwidth can be used for half of the communication time. Another reason to enforce a single channel in the control channel interval is inter-channel interference. When the transmitter of the interferer from the adjacent channel is much closer to the receiver than the transmitter of the sender, the receiver suffers from a high probability of packet errors [13]. Therefore, allowing service channels in the control channel interval degrades the reliability of safety messages in the control channel.

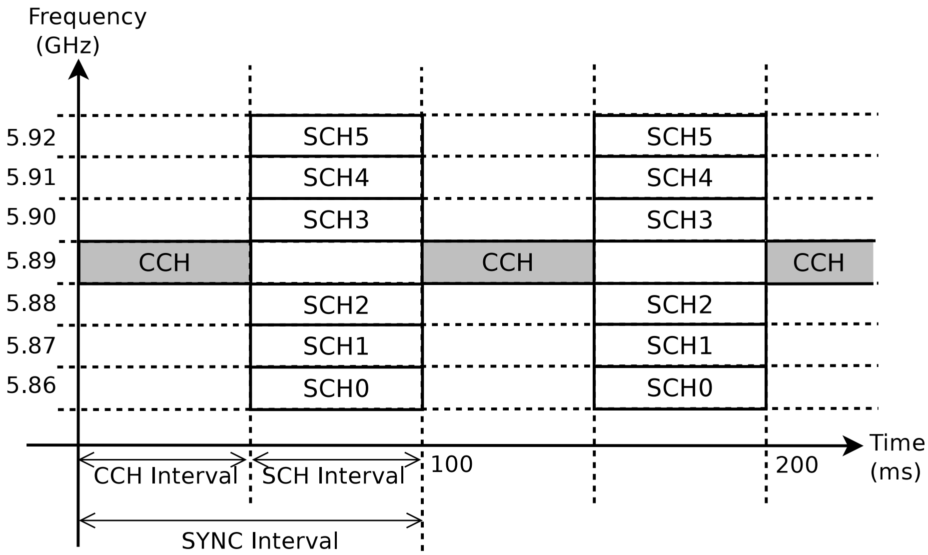


Figure 1: VANETs Channel Structure

While supporting applications by assigning different physical channels, another differentiating technique is used in each physical channel in MAC layer. Having six service channels implies that VANETs can support various types of applications in the future. Some applications require a higher quality-of-service (QoS) level than others. To support efficiently different QoS levels of applications, the IEEE 802.11p standard uses an enhanced distributed channel access (EDCA) technique that was originally proposed in the IEEE 802.11e standard. The goal of EDCA is to differentiate the channel access probability according to the QoS level of applications by assigning different contention window sizes and inter frame spaces. Higher priority applications have smaller contention window sizes and shorter inter frame spaces, which increases the chance of packets to be transmitted in contention with other nodes. The safety application messages can have the smallest contention window size and smallest inter frame space to be transferred with the highest priority.

2.2 Problems

In this thesis, two problems are addressed regarding the creation and delivery of safety messages. The first problem involves the delivery of a large amount of information in VANETs. Distributing a large amount of information such as multimedia messages in a single control channel results in much congestion. Transmitting multimedia messages through multiple channels to avoid this congestion becomes a feasible solution. However, using multiple channels in low vehicle density environments poses unique challenges and can produce connection failure if this issue is not carefully addressed. In this thesis, a network coding technique is introduced to solve this unique challenge for delivering multimedia content through multiple service channels in a low vehicle density situation.

The second problem involves the delivery of a safety message at an intersections. As the movement of vehicles should follow the topology of a road, the safety messages should be broadcast in all directions, especially at the intersections. The broadcasting methods in VANETs have been focused on removing collisions between broadcast packets. However, these methods limit the forwarding of safety messages to only one direction, which is not suitable at intersections. To solve this problem, a collision avoidance framework is introduced to remove the collision at the intersections while forwarding the messages in all directions.

2.3 Literature Survey

2.3.1 Broadcast

Safety messages are a key component in VANETs. There are two types of safety messages: cooperative warning messages and event-driven alarm messages [14, 15].

The cooperative warning message is a beacon message that each vehicle broadcasts periodically, which includes the position, speed and direction of a vehicle. With these messages, a vehicle can sense the existence and behavior of all neighboring vehicles. This cooperative message helps drivers or vehicles prevent the future accidents.

The event-driven alarm message is a message occurring after an accident happens. Vehicles forward this message to other vehicles to notify of an accident. With this alarm message, drivers or vehicles can know of accidents before they arrive at a location. In the medium access control (MAC) layer, all safety messages are transmitted by broadcast. Specifically, the periodic warning message uses one-hop broadcast and the event-driven alarm message uses multi-hop broadcast.

The broadcast technique that is used for transmitting safety messages has a weakness in reliability in the MAC layer. There are no efficient ways for receiving acknowledgement (ACK) packets from several recipients. If all recipients send ACK packets back to a sender, it makes packet collisions. In the IEEE 802.11 [16, 17], an ACK packet is replied back to a sender without backoff delay. Even though there was research [18][19] for receiving all ACK packets without collision, such methods have a problem in scalability. Even if it is possible to gather ACK packets from all recipients, such a method has a problem in scalability. Receiving ACK packets from a large number of recipients wastes a huge amount of bandwidth. Considering the high-density of vehicles on a road in vehicular networks, the scalability problem cannot be overlooked. Since these problems are difficult to solve, the IEEE 802.11 and IEEE 802.11p standard do not use any acknowledgement in broadcasts, which makes broadcast unreliable.

Besides the ACK packet problem, both safety message types have their own challenges. In one-hop broadcast for periodic messages, the congestion of a channel is a problem. For the safety message to be effective, the period between consecutive messages should not be too long. However, if the period is too small and the vehicle density is high, a channel becomes too congested from frequent beacon messages. In such congested channels, most packets are lost by collisions. To avoid congestions, methods using periodic beacons adaptively have been proposed.

In [20][21], the relation between beacon generation rate, traffic density, transmission power and the size of a beacon has been studied. As a result, it suggests the adaptive control of those parameters to increase beacon reception rate. In [22], an adaptive traffic beacon (ATB) method has been proposed, which changes the beacon interval adaptively not to influence other protocols. In [23], instead of a beacon interval, a contention-windows size is changed to avoid congestion. The contention-window size is adaptively changed according the vehicle density. Increasing the contention window size leads to better beacon reception or low collisions in increased traffic density.

Controlling transmission power is another approach to solving the congestion problem. The transmission power is related closely to channel congestion. If the transmission power is high, the coverage of a message increases. Then, all vehicles in the coverage contend together with the channel. On the contrary, if the power is low and the coverage is small, the number of vehicles to contend with becomes smaller. However, the coverage of information also becomes reduced, which is not useful since many vehicles cannot hear the important information. In [24], authors suggest D-FPAV algorithm, which maximize the minimum transmission power of beacon messages under a given beacon load. With this algorithm, vehicles can increase the transmission power up to a level where the network is not congested.

Multi-hop broadcast has a different challenge from one-hop broadcast. In multi-hop broadcast, a message needs to be forwarded by another vehicle. Which vehicles will relay a packet is an important question for efficient and reliable forwarding. After a sender broadcasts a message, all vehicles in the transmission range become a candidate to rebroadcast an original message. As the number of candidate increases, the collision probability also increases. Besides the relay selection, redundant rebroadcast is another problem. If vehicles rebroadcast the message that has been rebroadcasted by other candidate vehicles, the channel becomes flooded by redundant packets, which is called the broadcast storm problem [25]. In [25], several methods were proposed to solve the broadcast storm problem: probability-based, count-based, distance-based, position-based and cluster-based. In mobile ad-hoc networks (MANETs) context where the above methods were proposed on, it was hard to assume that all nodes have GPS devices and apply the position-based method. In VANETs, it is not difficult that a GPS device is included in a vehicle. Moreover, by the standards, all vehicles are assumed to have GPS devices, which make the position-based method easy to apply. In VANETs, besides the position-based method, there are two more approaches to be considered, which are a packet-exchange based method and a road-topology based method.

2.3.1.1 A. Position Based Broadcast

A common approach to solving the broadcast problem in multi-hop is to select the farthest node from a sender for forwarding a packet. When the farthest node is selected, a packet can arrive at the end point with the smallest number of hops, which reduces delay and bandwidth consumption.

In [26], authors proposed several methods to select the farthest node while avoiding packet collisions and redundant rebroadcasts: weighted p-persistence, slotted 1-persistence, and slotted p-persistence. Those methods assign different probabilities to nodes based on the distance from a sender to a node.

Smart broadcast method [27] uses a similar approach, but it controls a backoff-window size. The transmission range of a source node is divided by several sectors. The size of the contention window is different according to sectors. A sector that is farther from a source has smaller window size than the sectors that are closer to a source. With these different window sizes, vehicles in a sector that is far from a source vehicle have a high probability to rebroadcast. To find which sectors vehicles are belong to, vehicles use GPS devices. In [28], authors proposed the OppCast method, which uses an extra broadcast to increase broadcast reception rate. For the first broadcast, it selects the farthest node. For the second broadcast, it selects the node in the middle of a sector.

These methods would suffer from a high collision probability when the density of vehicles is high. For example, the vehicles in the farthest sector would contend with the smallest window size, which increases the collision probability highly. So, these methods are required to set the window size or the sector-length adaptively based on the vehicle density.

2.3.1.2 B. Packet-exchange Based Broadcast

Another famous method for resolving rebroadcast collisions is urban multi-hop broadcast (UMB) [29]. The UMB method resolves the collisions by exchanging packets between nodes. The UMB uses request-to-broadcast / clear-to-broadcast (RTB/CTB) packets to find out which node is farthest from a source node. This packet-exchange scheme is similar to request-to-send / clear-to-send (RTS/CTS) packet exchange in Wi-Fi networks. While RTS/CTS scheme can be used with only one recipient node, RTB/CTB scheme can be applied for multiple nodes. In the UMB, a sender broadcasts a RTB packet. The position of the source node is included in an RTB packet. After receiving an RTB packet, nodes reply with a energy-burst (channel-jamming) signal to the sender. Its purpose is to be sensed by other nodes. The duration of the signal is proportional to the distance from a sender to a node. The longer the distance, the longer the duration of the signal. After sending a signal, nodes start sensing signals from other nodes. If a node can sense a signal from another node, this indicates that there is another node that is farther than this node from a source node. Nodes that sense the signals drop their opportunity to rebroadcast. If a node cannot sense any signals, this node is the farthest node from a source node. Then the farthest node has opportunity to rebroadcast. With this protocol, the UMB solves the rebroadcast collision problem. Also similar to RTS/CTS, RTB/CTB can avoid the hidden node problem.

One weak point in the UMB scheme is the extra process in exchanging packets. If the size of packet to be broadcasted after RTB/CTB packet exchange is small, the packet exchange becomes an overhead. This extra process brings an overhead when it is used at the intersection. Since the UMB method uses the packet exchange at each direction, it is not suitable to forward packets to all the directions at the intersection.

2.3.1.3 C. Road-topology Based Broadcast

The road topology affects the broadcast scheme. As vehicles move according to the road topology, safety messages also should follow the road topology. However, when the

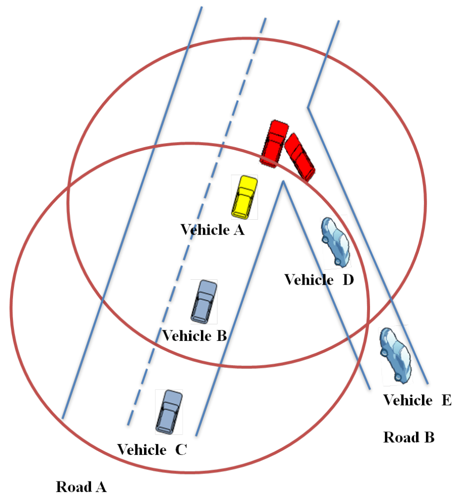


Figure 2: An Intersection Example

previous broadcast schemes are applied at an intersection, it is difficult to forward messages to all directions since those schemes focus on avoiding collisions by selecting one forwarding node. In Figure 33, a safety message cannot be forwarded to all directions.

When node A starts broadcasting, both node B and node D receive the message and try rebroadcasting it. To avoid a collision, one node needs to be selected as a forwarding node. If a position-based scheme is applied, node B will be selected since the distance from node A to node B is longer than to node D. When node B rebroadcasts, node D will not broadcast since it receives the same message from node B. In this case, the message is forwarded only to the direction of road A and all vehicles in road B cannot receive this safety message.

In [29], a method based on a road-side unit (RSU) is proposed. Authors assume that roadside units exist at every intersection and those units know about each direction of a road. When a safety message arrives at an intersection, a roadside unit (for example, a traffic signal which is equipped with a VANET-enabled device) is responsible of forwarding message to each road direction. However, it is difficult to suppose roadside units are available at every intersection, especially in the initial deployment phase of VANETs.

In [30], authors use the position and angle of vehicles to decide if the received message should be forwarded or not. When a vehicle sends a safety message, it includes its direction and position. After other vehicles receive the message, they can find out an angle between the sender and themselves based on their direction and position. If the angle is large enough, vehicles decide if the safety message comes from a different side of an intersection. Even though it is the same safety message that they already receive, they start rebroadcast since the message was aimed for another road direction.

Both of the above methods are successful to forward to each direction of roads. However, they did not consider the effectiveness of broadcasting scheme. In [29], authors use RTB/CTB packets. The traffic signal at the intersection starts RTB/CTB handshaking to every direction of road. As the number of roads increases, the increased handshaking packets become an overhead. In [30][31], authors use distance-based broadcast. The distance-based broadcast has higher probability of collision as the number of vehicles increase. At the intersection, the number of vehicles increases as the number of roads increases. To start rebroadcast with same back-off probability, the collision rate would increase by as many as the number of different roads.

Later in this thesis, this intersection problem is studied and the multi-vehicle selection broadcast (MSB) method is proposed. The MSB method makes it possible to specify multiple vehicles that join the rebroadcast process and remove the collisions between the specified vehicles. With the MSB protocol, the delay to cover all directions at the intersection can be reduced.

2.3.2 Multiple Channels

The usage of multiple channels in VANETs has been an interesting research topic. There are several methods to exploit multiple channels [32, 33, 34, 35] in mobile ad-hoc networks. These methods differ in how many radios are used and how devices contend for a channel. Among these methods, the common channel method [35] is appropriate since it splits an interval in two sub-intervals like the CCH and SCH interval in VANETs.

The common channel method is based on a single transceiver. This method uses one control channel for negotiating the selection of a data transfer channel. After finishing the negotiation, the pair of nodes moves to the selected channel. After they finish data transfer, they come back to the control channel. Compared with a dual-transceiver method, the total throughput becomes lower but the advantage of this technique is it uses a single transceiver. The channel structure of VANETs is suitable to use this technique since all vehicles should reside on CCH and select one of the SCHs depending on the exchanged information during the CCH interval. However, the intensive usage of the control channel becomes a bottleneck as the number of nodes increases.

Some research focus on the specific channel structures of VANETs. In [36], authors pointed out that during the CCH interval, the six service channels are completely idle. To increase bandwidth usage, a roadside unit (RSU) based method was proposed. With the help of the RSU, vehicles can use any channels even in CCH interval. When there is a critical safety message, the RSU catches the message and delivers it to each vehicle. This method cannot be applied outside of the transmission range of the RSU. If the deployment of RSUs will be rare in the initial phase of VANETs, this method cannot cover most roads.

In [37], a cluster-based approach was proposed. A cluster is formed within the communication range of a vehicle. In the cluster, one cluster-head vehicle is selected and can control other cluster-member vehicles. After a cluster-head vehicle is selected, the head vehicle can assign appropriate channels for other vehicles, which enables an efficient usage of channels. However, considering the dynamic behavior of fast-moving vehicles, the duration of cluster will be short. This short duration requires vehicles to form new cluster frequently, which uses extra packets to set up a cluster and select new header vehicles.

Another approach for using multiple channels is using directional antennas. Directional antenna provides a good technique for increasing the transmission range, which reduces delay to the end point when packets are relayed through multi-hop. When a direction of a beam is selected wisely, the spatial reuse also can increase, which increases the available bandwidth for vehicles to use. Different from small nodes in sensor networks or MANETs, a vehicle has enough space to equip various antennas and power to handle complex processing. In [38], the pair of vehicles share their beam-direction information and available channel information. Other vehicles also can choose the available beam directions and channels that avoid collisions from existing communication, which can maximize bandwidth reuse. However, to use a directional antenna in multiple channels, the information regarding which channel and which direction to be used should be exchanged frequently.

There is research considering cellular networks such as 3G or LTE as another channel in VANETs. One approach is to replace the communication layer from IEEE 802.11p to cellular networks [39][40][41]. If cellular networks are used instead of IEEE 802.11p in VANETs, the advantages are well established network and wide-spread coverage. However, in the cellular networks, the capacity of supporting safety beaconing messages is not as efficient as IEEE 802.11p [42][43]. The IEEE 802.11p VANETs is based on CSMA/CA which implies a beacon from a vehicle can reach to all neighboring vehicles easily since the beacon is transmitted by broadcast. However, in cellular network, the beaconing message must be uploaded to a base station and needs to be broadcast using the download link. This separate uplink/downlink beaconing is not efficient.

Another approach is using the cellular network as a secondary communication channel. This approach focuses on a high-speed connection to the Internet through LTE. To access the Internet, vehicles rely on the vehicle-to-vehicle (V2V) communication. V2V communication requires some vehicles to relay packets. If there are not enough vehicles, it is difficult to maintain the communication. Also when the vehicle density is extremely high, the channel starts being saturated and the throughput starts falling, since V2V communication is based on CSMA. In this case, the hybrid solution (IEEE 802.11p with LTE) becomes an attractive option. In [44], the authors suggest using bandwidth of neighboring vehicles to download contents from Internet. Since the bandwidth to each vehicle is limited, the neighbor vehicles download the contents together using their LTE connection. Then, they forward the contents by V2V communication since the V2V communication has better bandwidth.

As the previous example, the use of cellular network to access the Internet will be an interesting research topic. However, related to the safety message, IEEE 802.11p cannot be replaced by the cellular networks.

For the multiple channels, one interestign approach is aggregating multiple channels. This is called channel aggregation [45][46][47]. This channel aggregation is a new feature in LTE-advanced technology which improves throughput rapidly. This channel-combining feature is not supported in the current IEEE 802.11p devices. However, the similar technology is already used in IEEE 802.11n such as channel bonding [48]. Since the device of VANETs can easily adapt the IEEE 802.11 technology, it is not impossible for IEEE 802.11p to adapt IEEE 802.11n technology in the near future. If the channel aggregation or boding technology is supported, a large amount of multimedia safety message can be delivered faster through SCH intervals. As the current devices, even though there are multiple SCH channels, only one channel should be used for delivering the safety message. The channel aggregation or boding would be a promising solution to increase channel throughput in VANETs as it has been proved in cellular networks or Wi-Fi networks.

While the above research addresses the efficient usage of channels in VANETs, the congestion of a control channel still remains as a problem to be solved. If the required amount of data for safety applications becomes large, the congestion becomes severe. Multimedia traffic is a good example of the application involving a large amount of data. To avoid the congestion of a control channel during the transfer of large amount of information, a way of using multiple channels for large information is proposed in the preliminary research. In that research, large information is transferred not only in the control channel but also in the service channels. Using service channels makes more bandwidth available for other safety applications versus using only control channel.

2.3.3 Network Coding in VANETs

Network coding is a packet-level coding technique to mix information from every packet enabling each packet to have information from other packets. Originally network coding was proposed for efficient multicast protocol in [49]. Two packets are under an exclusive-or (XOR) operation creating one coded packet. A receiver can decode each packet if it has one coded packet and any one of original two packets. This coding technique helps reducing the complexity of multicast routing as well as achieving the maximum data transfer rate from a source. This characteristic brings many interests on the network coding area [50][51].

One area where network coding is applied well is peer-to-peer network (P2P) [52]. In P2P, one challenging problem is which pieces should be shared between peers. If the pieces are selected wrong, some pieces are duplicated or depleted in peers. In [53], the authors describe this as a coupon selection problem and suggest network coding to solve this problem. With network coding, nodes can share pieces without a difficult selection process, which simplifies the process. Also, since the information is distributed well over all nodes, even in the case when the original source node disappears from the P2P network, the content can be delivered to all other nodes better than the case when no coding is used [54][55].

Besides the wired network, network coding has been used in wireless network [56, 57, 58] for increasing throughput as well as reliability. Especially when a large amount of information is delivered by broadcasts over wireless channel, network coding becomes useful. In broadcast, as explained in the previous sections, it is difficult to get acknowledgements from all recipients. A typical way of increasing reliability is to transmit packets with lowest rate. However, with the help of network coding, reliability can increase by generating extra packets. With network coding, a receiver can recover information only if receiving the original number of packets even though many packets are missing over a wireless channel. So, when a source generates enough network coded packets, receivers can recover original information successfully.

While there are some nonlinear network coding methods [59][60], most network coding methods are based on linear network coding [61][62]. In linear network coding, a sender can generate output information by linear algebraic operations to original input information. The size of output, M, is greater than or equal to the input size, N. The original information to be sent is described by a vector $X = [x_1, x_2, ..., x_N]$. Then, a vector of coefficients is selected randomly in the Galois field $GF(q)$ as $C = [c_1, c_2, ..., c_n]$. After a linear matrix operation, the output vector $Y = [y_1, y_2, ...y_M]$ is generated. It can be shown as Equation (1).

$$\begin{bmatrix} y_1 \\ \vdots \\ y_M \end{bmatrix} = \begin{bmatrix} c_{11} & \cdots & c_{N1} \\ \vdots & \ddots & \vdots \\ c_{M1} & \cdots & c_{MN} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix} \tag{1}$$

In VANETs, multimedia delivery is a good application for using network coding. In [63], a method for disseminating multimedia safety applications using network coding has been suggested. A source node divides information into groups of blocks, each of which has multiple packets. A source node generates network coded packets from packets belonging to a block. After receiving these packets, receiving nodes start broadcasting periodically what they have as well as the information of the block id and the number of coded packets (which is called rank). Node A receives packets from node B and can find if node B has less information than node A based on the block id and rank. Then, node A sends packets to node B to help node B to collect more coded packet.

In [64], a file sharing technique between vehicles has been proposed. A seed vehicle that has files advertises them through a file descriptor. When peers request a file, a seed vehicle divides a file into N blocks and sends a network-coded block to peers. Since the blocks are network-coded, a peer can recover a file only if it receives N blocks from any seed or peer vehicle. When a vehicle requests a coded block, it attaches a nullspace vector of coded blocks that it already has. The nullspace vector is a vector in the nullspace spanned by all coefficient vectors in the stored blocks in a requesting vehicle. When a peer vehicle receives the request with a nullspace vector, it responds only if its coefficient vector is not orthogonal to the nullspace vector from a requesting vector.

While other network coding schemes are applied on the packet level, in [65], a symbol-level network coding (SLNC) is proposed. In the SLNC, network coding is applied with symbols in the PHY layer of a packet. The error rate of symbols is smaller than that of a packet, which enhances the successful packet acceptance rate as well as throughput. In [66], the SLNC is used for streaming multimedia services. Loads are divided by sectors that have an equal length. A vehicle at the center of the sector starts as a coordinator which decides which vehicle relays multimedia packets. Each vehicle reports its status regarding how much multimedia information it has. Based on that information, the coordinator selects a relay vehicle that has the most useful information for others. The selected relay uses symbol-level network-coding to increase throughput. As a result, the average buffering level becomes lower than other methods. This method depends on the periodic advertisement from neighboring vehicles. Also it does not consider the multi-channel structure. Since vehicles select a service channel randomly, the coordinator should be selected at each channel and all information need to be gathered again since vehicle topology has been changed.

In [67], a way of getting large-sized Certificate Revocation List (CRL) through network coding and multiple channels is suggested. Considering the number of compromised vehicles across a nation, the size of CRLs becomes huge. To share the large file efficiently, authors suggest the most pieces broadcast (MPB) method, which gives highest priority of broadcast to a node that has most pieces.

Most network coding or multimedia distribution techniques consider a single channel as well as depend on advertising from neighboring vehicles. In the next preliminary study, a method is proposed to use multiple channels, which does not require advertising. The proposed method is useful in delivering large amounts of information through multiple channels.

CHAPTER 3

MULTI-HOP SAFETY MESSAGE FORWARDING IN MULTI-CHANNEL FOR VANETS

3.1 Introduction

As introduced in chapter 2, the VANETs standards have distinguished channel structures. The VANETs standard [11] supports six service channels (SCHs) and one control channel (CCH). Each of these seven channels has a 10 MHz bandwidth and a 50 ms interval sharing a 100 ms interval equally. Vehicles are free to join any one of six service channels during SCH intervals. However, all vehicles should stay on a single control channel during CCH intervals for disseminating or listening to safety information. In addition, periodic beacon messages from vehicles will be broadcasted in this CCH channel. Even though the standard supports multiple channels, a lot of traffic will be disseminated on a single control channel.

Usually safety information is transmitted in a short-text message format. This short message ensures fast and reliable delivery in restricted (e.g., $\leq$ 10 MHz) and unreliable channels in VANETs. Alternatively, users can also enjoy the benefits of using rich multimedia content (e.g., video, audio) to easily recognize and understand the information. Some studies already address the significance of multimedia information in safety applications [63, 68].

Transferring a short safety message in the control channel will not cause a problem. However, transferring a large amount of information such as multimedia content in the control channel will lead the channel to be severely congested. Theoretically, VANETs can provide up to 60 MHz of bandwidths if all SCH channels are used. However, this support is limited to the SCH interval. If the multimedia content can be delivered through the SCHs, the congestion of the CCH can be reduced.

If only one of the SCHs is used for delivering multimedia messages, it uses one-sixth of the total bandwidth in the SCH interval. To maximize the utilization of available bandwidth, distributing packets through all the channels in the SCH interval is more effective than using just one channel.

In this thesis, the proposed algorithm for utilizing multiple channels is to *divide* the entire multimedia safety application information into packets considering the number of available SCHs and *deliver* the packets in each SCH. This scheme is called *divide-and-deliver*. This approach minimizes the amount of bandwidth used in each channel when delivering multimedia messages. Moreover, vehicles in each channel can forward the divided small packets to the other vehicles through multi-hop forwarding. However, if a single channel is used for delivering a large amount of information in the SCH interval, a vehicle cannot use multi-hop forwarding since there is not much bandwidth left. With the multi-hop forwarding, the *divide-and-deliver* scheme, however, can deliver multimedia messages quickly to the target vehicle or infrastructure with fewer CCH intervals.

Another advantage of the *divide-and-deliver* algorithm is a longer one-hop broadcast distance even though it does not use multi-hop forwarding in SCH intervals. This advantage is due to the small number of packets that a vehicle receives in each channel. More details of *divide-and-deliver* will be explained in the chapters that follow.

In this chapter, how the *divide-and-deliver* scheme is used in VANETs will be discussed thoroughly. The delay reduced by the proposed approach is compared to the conventional single channel method. The comparison will be done by analyzing the delay and showing the simulation results. This chapter proceeds as follows: In section 3.2, the DD algorithm is described. In section 3.3, the simulation results and analysis are presented. In section 3.4, the conclusion is added.

3.2 Algorithm

3.2.1 Protocol

The concept of the *divide-and-deliver* scheme involves dividing the information into smaller packets and delivering them on each channel. If there are N channels and the size of information is S bytes, each channel will deliver S/N bytes. If the S/N is larger than the maximum size of a packet, they will be delivered as several packets.

Until packets arrive at the target location, the packets will go through both SCH and CCH intervals repeatedly. After vehicles receive packets in CCH intervals, they need to select one of the SCH channels while preparing the next SCH interval. For the selection of the next SCH channel, a common rule between vehicles should exist regarding which channel a vehicle can choose and which packets they can deliver. Without that rule, the packets cannot be delivered to the target location successfully.

For example, there is a case when some vehicles in different channels select to send the same packet. Since vehicles cannot know which packets are sent in other channels, they could select the same packets with other vehicles in other channels. Due to the wrong selections, the same packets will be forwarded in some channels. The, the duplicated set of packets will arrive at the target location. When all the vehicles select the same channel, unsuccessful delivery can occur as well. This would rarely happen when the vehicle density is relatively high enough such that the probability of choosing the same channel among all vehicles is low. However, when the vehicle density is low, there is a case when all the vehicles select a same channel. This low density problem will be described in the next chapter separately.

Figure 3 shows the case of duplicated packets without a rule. For example, the number of original packets is four. In the T1 interval, all vehicles receive four packets. In the T2 interval (SCH), vehicles select one of the channels and decide which packet they will send in the channel. The number inside a shape (rectangle or hexagon) represents the selected packet. Each packet is delivered to another vehicle in the T2 interval. In the

T3 interval (CCH), a vehicle receiving a packet in the T2 starts broadcasting the received packet. Then, the packet 4 has been missing while the packet 3 is duplicated. As seen from this example, *divide-and-deliver* scheme could not forward the original information to the end point without a rule that restricts the selection of packets to be forwarded in a given channel.

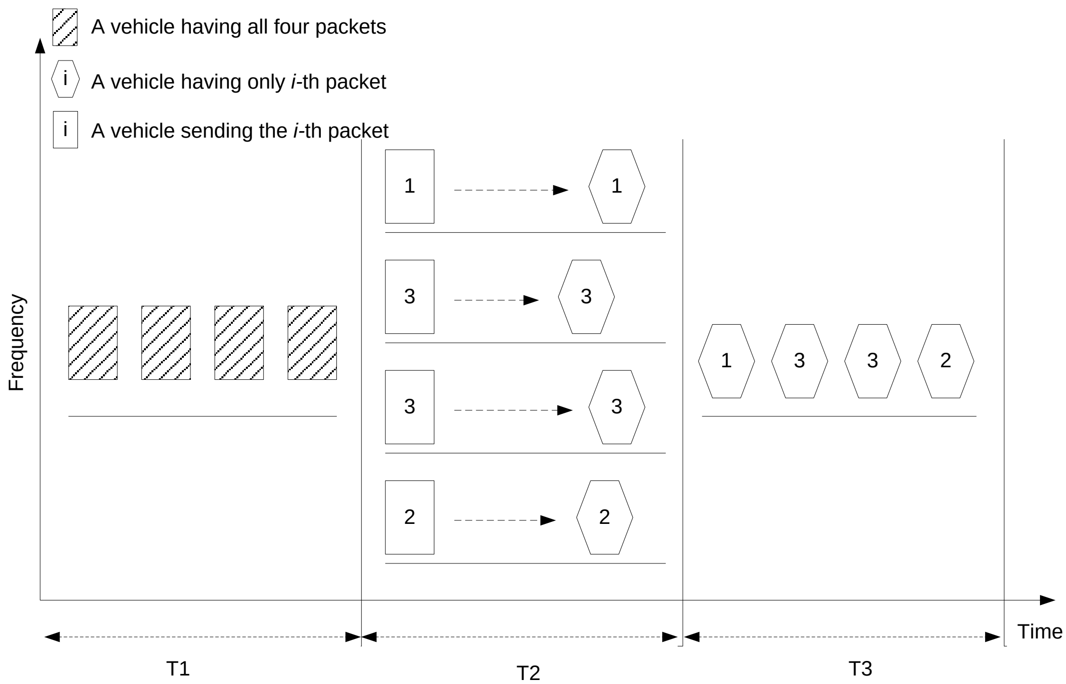


Figure 3: Duplicated Packets over Multiple Channels

To solve this problem, a simple rule is used in this thesis. A packet should be delivered through the same SCH channel from the first SCH interval until it arrives at the target point. To apply this rule, a packet needs to include the previous SCH channel information. Then, a vehicle knows which channel the received packets came from and the packets should be delivered in the next SCH interval. This rule restricts the available channels for a vehicle to select in SCH intervals. When a vehicle is selecting an SCH channel, it investigates all the packets it receives and creates a list of previous SCH channels. Then, it chooses one of the channels from the list for the next SCH channel. If a vehicle did not receive any packet to be rebroadcasted, it can choose any SCH channel freely. With this rule, the event that sending duplicate packets across channels as shown in Figure 3 can be removed.

One exceptional case of this rule is the first SCH interval after a source vehicle broadcasts in the first CCH interval. Since packets have no previous SCH channel information in the first CCH interval, a vehicle can choose any SCH channel. After moving to a SCH channel, a vehicle needs to create packets to be delivered in that channel. If a vehicle receives S bytes from a source vehicle, a vehicle will divide the information by the number of channels, N. Then, there are N sets of information from I_1 to I_N. A vehicle chooses a I_i based on its current SCH channel. For example, if a vehicle is in SCH_3, the vehicle will choose the I_3 and deliver the S/N bytes.

The vehicles selecting the same SCH channel need to contend with each other to rebroadcast the received packets. The contention will be done by a sector-based algorithm [27][69][70][71], which allows a higher priority of broadcast to the vehicle which is farthest from a source node. This algorithm helps deliver a packet with a longer one-hop distance, which results in reducing end-to-end delay.

When a vehicle broadcasts packets, the packets will include the maximum hop counter as well as the current hop counter. These counters control the number of hops in a channel. The current hop count increases whenever packets are forwarded by a new relay vehicle. The relay process will be repeated until the current hop counter becomes equal to the maximum hop counter. For the single-hop case where the maximum hop counter is one, no more relay occurs after the first broadcast from a selected relay node in SCH intervals.

After the relay process is done in SCH intervals, the vehicles receiving packets from the last relay node wait until the channel interval changes to the CCH interval. Then, the vehicles broadcast the packets in the next CCH interval.

Figure 4 describes the above algorithm.

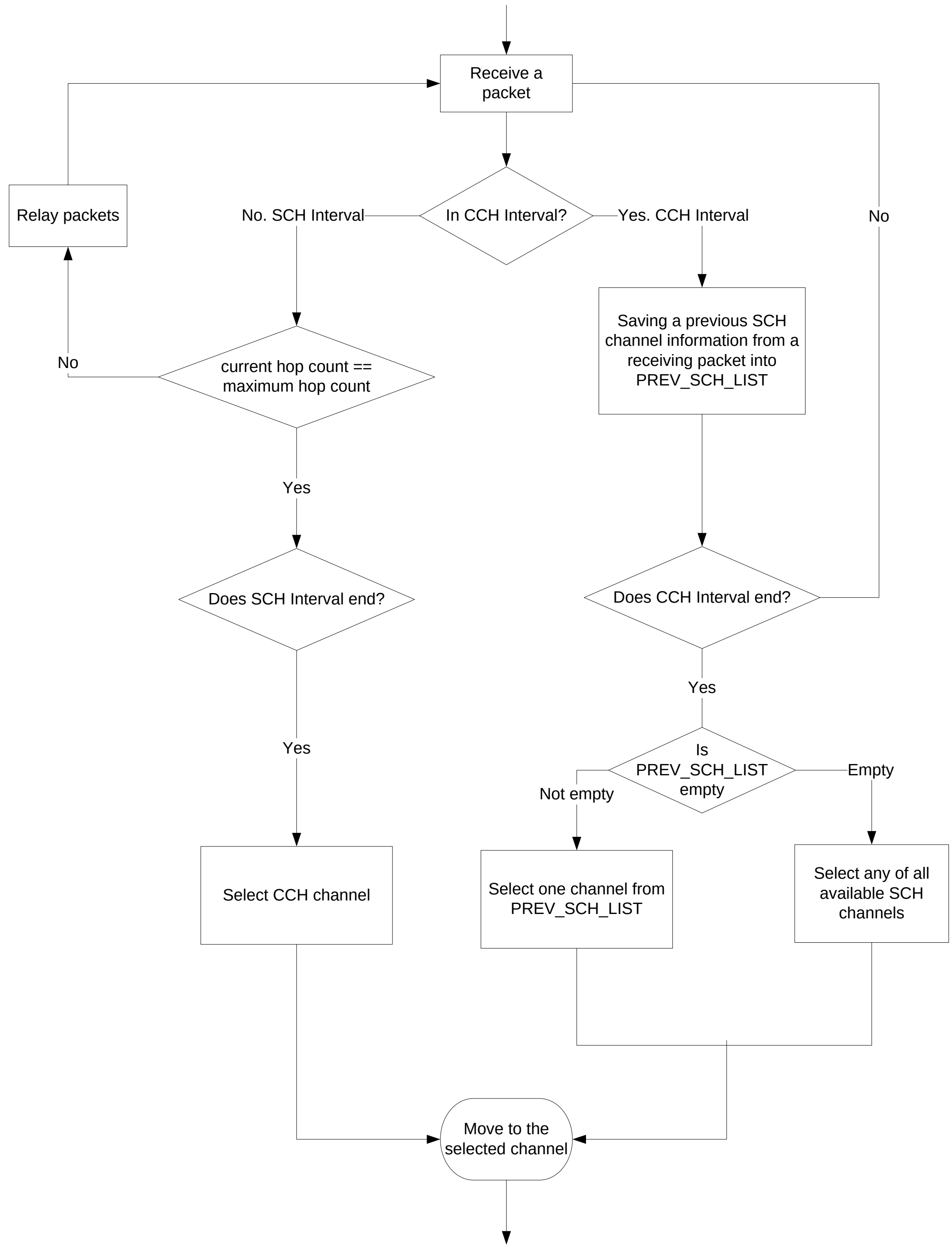


Figure 4: Flowchart for Channel Selection in Divide-and-Deliver Method

3.2.2 Multi-hop Forwarding in SCH Intervals

The *divide-and-deliver* method can use multi-hop forwarding in SCH intervals. For the *divide-and-deliver* method, the number of hops in SCH interval relies on the size of information. If the amount of information to be delivered is small, the divided information to be delivered in each channel is much smaller. Then, more bandwidth will be available and more hops will be possible in each channel.

When the size of information is large enough to occupy all the bandwidth of CCH channel, the number of hops in each SCH channel can be decided by the number of available channels.

The amount of information is S bytes and the amount of information in each channel is S/N, where N is the number of channels. The maximum number of hops in each channel can be calculated from dividing the duration of interval by the transmission time of S/N. The transmission time of S bytes can be calculated based on the specification [12], which can be expresses as $T_{tr}(S)$. Then the maximum number of hops in each channel, H_{max}, is

$$H_{max} = \frac{T_{intvl}}{T_{tr}(S/N)} \tag{2}$$

T_{intvl} is the duration of an interval. Since the goal of the equation is finding out the upper-limit of the maximum hops, some assumptions have been added. The delays due to added headers and back-off contentions will be ignored. Then, $T_{tr}(S)$ becomes a pure transmission time of S bytes. In that case, $T_{tr}(S/N)$ can be rewritten to $T_{tr}(S)/N$.

If the transmission of S bytes in a channel is long enough to occupy the whole CCH interval, this is the maximum size of information that can be delivered through all the intervals. Then, the maximum (upper limit) hops in SCH interval of *divide-and-deliver* becomes Equation (3).

$$H_{max} = \frac{T_{intvl}}{T_{tr}(S)/N} = \frac{T_{intvl}}{T_{intvl}/N} = N \tag{3}$$

In Equation (3), the maximum number of multi-hop in SCH intervals becomes the number of channels. This implies that in SCH intervals, *divide-and-deliver* can deliver information N times faster than a single channel method. This speed-up can increase if VANETs can provide more channels. It shows the capability of *divide-and-deliver* using multiple channels efficiently.

Within the maximum hops, the *divide-and-deliver* method can deliver information via multi-hop, which decreases the end-to-end delay. The delay to the end-point with multi-hop can be described by the following equations.

T_{cch} = duration for CCH interval

T_{sch} = duration for SCH interval

T_{sync} = duration for sync-interval containing both CCH and SCH interval

D_{hop} = average distance for one hop

D_{end} = distance to the end device

T_{end} = delay to the end device

N_{hpf} = the number of hops in a frame

H_{max} = the number of hops to the end device

N_{sync} = the number of sync intervals until a packet arrives at the end device

N_{ch} = the number of channels

p = the number of total packets

$q = p/N_{ch}$

N_{lh} = the number of hops in the last interval

$$T_{sync} = T_{cch} + T_{sch} \tag{4}$$

$$H_{max} = \lceil \frac{D_{end}}{D_{hop}} \rceil \tag{5}$$

$$N_{sync} = \lfloor \frac{D_{end}}{N_{hpf} * D_{hop}} \rfloor \tag{6}$$

$$N_{lh} = H_{max} - N_{sync} * N_{hpf} \tag{7}$$

$$T_{end} = T_{sync} * N_{sync} + T_{remain} \tag{8}$$

$$, where \quad T_{remain} = \begin{cases} T_{tr}(S) & \text{if } N_{lh} = 1 \\ T_{cch} + T_{tr}(S/N) * (N_{lh} - 1) & \text{if } N_{lh} > 1 \end{cases}$$

As seen in Equation (6) and (8), the delay to the end device decreases as the number of hops in the service channel increases and the distance of a hop increases. To deliver packets faster to the end point, either the multi-hop delivery in SCH intervals or the longer one-hop distance is required. The multi-hop delivery is available only within the *divide-and-deliver* method. In the following section, the one-hop distance between two methods will be investigated.

3.2.3 Longer One-hop Distance

The distance of a hop depends on the vehicle density. If the density is higher, there is more chance that a vehicle is located near the edge of the radio range. These far-located vehicles increase the distance of a hop. The increased hop-distance reduces the total number of hops to the target location and reduces the total delay.

This increase of hop distance by the density of vehicles is fair to both *divide-and-deliver* method and single channel method, since they will use the same algorithm in a given channel such as a sector-based algorithm. Usually, these broadcast-relay algorithms select the farthest vehicle form a source to relay a packet. When the vehicle density is higher, the hop distance for both methods becomes larger since there is higher chance that a vehicle exists at the edge of a radio range. However, the hop distance of these two methods is different even in the same vehicle density. The one-hop distance in the *divide-and-deliver* method is longer than the single channel method. In the *divide-and-deliver* method, the vehicles receive and deliver a smaller number of packets than the single channel method. The difference in the number of packets to be received affects the one-hop distance as following explanations.

When a source vehicle broadcasts multiple packets, all the neighboring vehicles receive these packets. Then, the vehicles that receive all the packets successfully start contending a channel for rebroadcasting the packets. Since only the vehicles that receive all the packets successfully will start rebroadcasting, the hop distance relies on the location of vehicles that receive all the packets successfully. If the wireless channel condition is good, the vehicles at the edge of radio range would have a chance to receive all the packets successfully. If the wireless channel is poor, the vehicles that receive all the packets successfully would be closer to the source node.

While the wireless channel status is identical in both methods, the rate of successful reception is controlled by the number of packets. With a same channel status, the chance of receiving a small number of packets without an error is higher than receiving a large number of packets without an error. So, for the comparison of two methods, the number of packets becomes the factor making a difference to the hop distance. In a channel, the single channel method delivers a total of P packets while the *divide-and-deliver* methods deliver P/N packets, where N is the number of service channels. So, in the *divide-and-deliver* method, there is a greater chance that the selected vehicle for relaying safety information is closer to the edge of radio range than in the single channel method.

This increase of hop distance results in a packet arriving at the target point with a smaller number of hops. Consequently, the smaller number of hops brings reduced delay. The simulations of these metrics will be shown in the next section.

3.3 Results

In this section, the delay between *divide-and-deliver* (DD) method and the single channel method (SC) will be shown by simulations.

For the simulation, NS-3 is used [72]. The packets are generated at 0-km point and delivered to the end point at 10-km. The arrival of packets is measured every kilometer, which shows the delay at each kilometer. The size of the packet is 1K byte and the number of packets sent in the common channel interval is 12. This amount of packets prevents multi-hop delivery in a single channel since it occupies more than 70% of the bandwidth in a channel.

For the high density environment, three density settings are used: 190, 240 and 290 vehicles per kilometer, respectively. To compare the delay and reliability, two algorithms (DD and SC) are used as described in the previous sections.

First, the delay of single hop case in SCH intervals will be investigated. Then, the delay of multi-hop case of the DD method will be explained.

Figure 5 shows the delay of single hop case in SCH intervals for both methods. The delay is measured at each point with various vehicle densities.

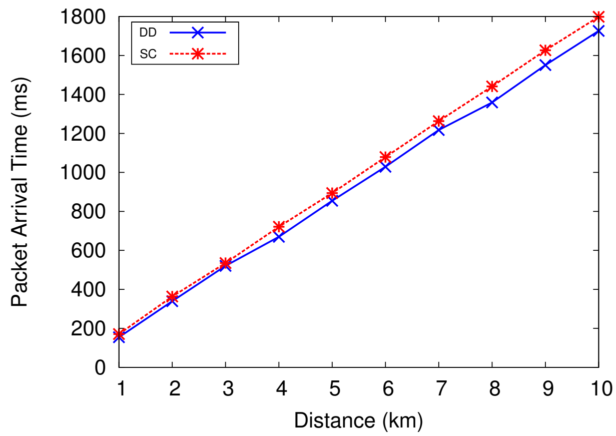
The delay increases as the distance (or location) of the measuring points increase.

In higher density situations, packets arrive at each measuring point faster than lower density case. For the comparison, Figure 6 shows the difference of packet delay at the same measuring point (10 km point) with different densities. Even though the difference is small, the delay decreases as the density increases. This delay change according to the density is seen in both methods.

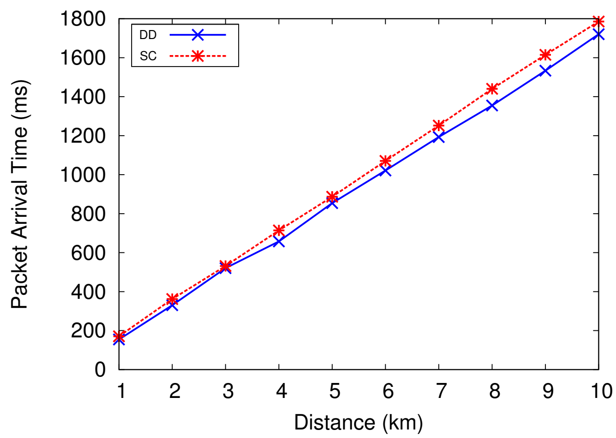
This difference in delay is due to the distribution of vehicles. When vehicle density is high, there is higher chance of vehicles that exist at the edge of radio range from a source vehicle. These vehicles farther from a source vehicle have a longer hop distance and the total delay from the source to the final destination will be shorter. Therefore, the performance of total delay from the source to the destination has a direct correlation with the one-hop distance. Figure 7 shows the change of one-hop distance when the vehicle densities vary. As expected, the hop distance increases as the densities go higher.

In SCH and CCH intervals, distinctive differences in one-hop distance can be observed due to the vehicle density differences between the two channels. Since all the vehicles stay on the same channel in CCH intervals, the vehicle density is higher in CCH intervals than SCH intervals. So, even in the same vehicle density, there is another density difference according to the intervals. The hop distance in the CCH intervals is higher than in the SCH intervals. Figure 8 shows the hop-distance in CCH and SCH intervals, respectively.

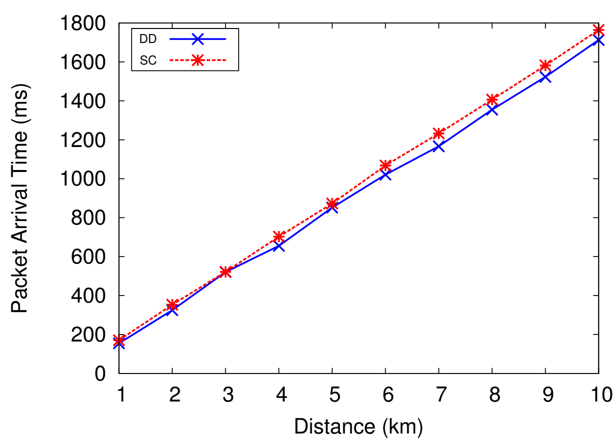
When the higher vehicle density reduces the delay in both methods, there are differences between two methods in the same density. As shown in Figure 5 and Figure 6, though the delay difference is small, the DD method has less delay than the SC method. The small delay in the DD method is explained by the longer one-hop distance of the DD method in Figure 7. This longer hop-distance is caused by the difference in the number of required



(a) Packet Arrival Time with Vehicle Density 190 per km



(b) Packet Arrival Time with Vehicle Density 240 per km



(c) Packet Arrival Time with Vehicle Density 290 per km

Figure 5: Packet Arrival Times

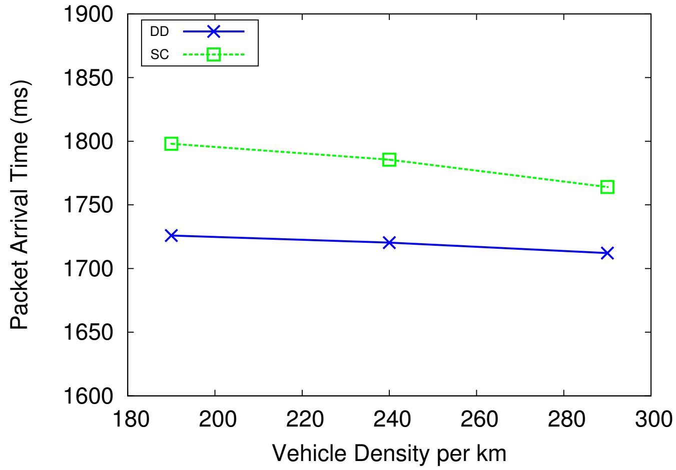


Figure 6: Delay vs. Density

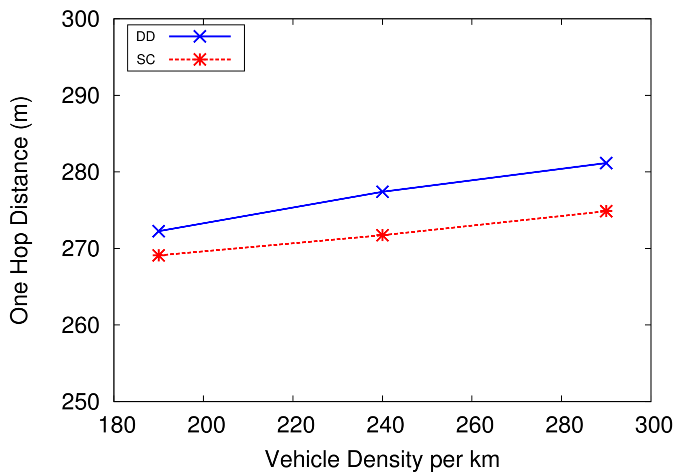


Figure 7: Hop Distance Change

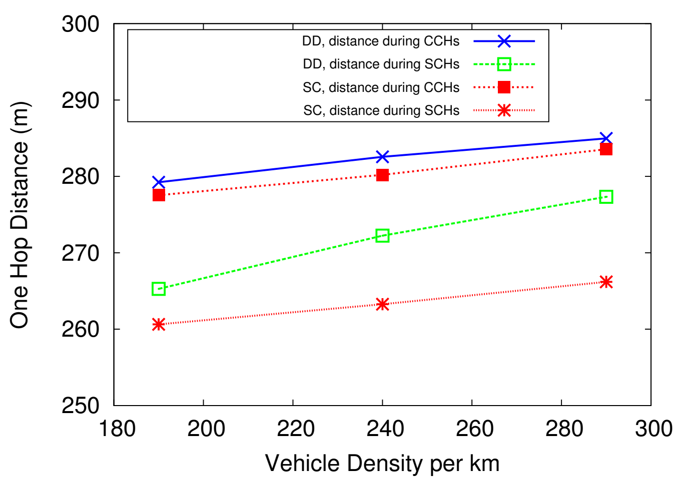


Figure 8: Hop Distance in Intervals

receiving packets in each method. The DD method requires receiving less packets than the SC method.

When a wireless channel status is good, the difference between two methods can be small. However, in a real situation, the vehicle at the edge of radio range would have a low Signal-to-Noise Ratio (SNR) value. Also the wireless channel for mobile communication includes fading. So, to compare the performance of two methods, considering the various bit error rates (BER) is useful. To show the effectiveness of each method, three metrics (one-hop distance, number of hops and packet arrival time) are compared and all these metrics are closely related.

Figure 9 shows the one hop distance according to different BERs. When the BER is good enough, both the DD and SC method have a similar one-hop distance since there is a small chance of a packet dropping. However, as the channel becomes worse, the BER deteriorates accordingly and the one-hop distance between the transceiver changes. Generally, the one-hop distance starts decreasing in both methods. However, while the distance decreases slowly in the DD method, the SC method shows a rapid decrease. The slow decrease shows the DD method is resilient in low BER situations mostly because of the reduced packets will reduce the probability of packet loss in the DD approach. This resilience is connected to a longer one-hop distance in the DD method. The one-hop distance is decided by a relay vehicle. The relay vehicle is usually selected from the vehicles that are located closely to the edge of the radio range. Those vehicles usually experience lower BER than other vehicles that are closer to a source vehicle. So, the better performance in the low BER implies the better chance of the vehicles at the edge of the radio range receiving packets successfully.

Figure 10 shows the number of hops when packets arrive at the target device which is 10 km away from the packet origination. The DD has a smaller number of hops since it has a longer one-hop distance.

Figure 11 shows the delay to the target point in different BERs. By the larger one-hop

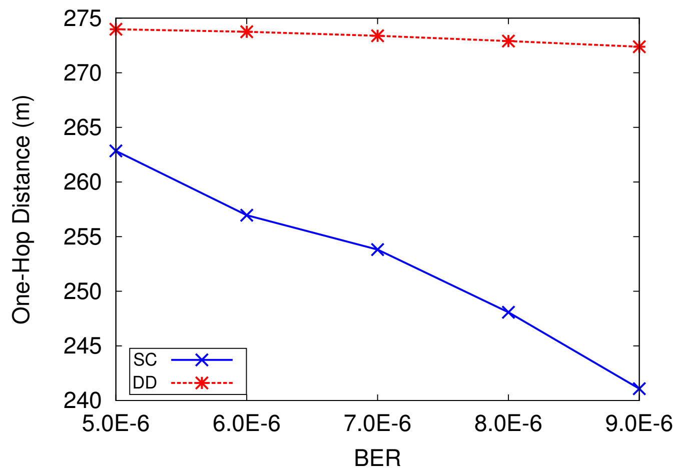


Figure 9: One Hop Distance by BER

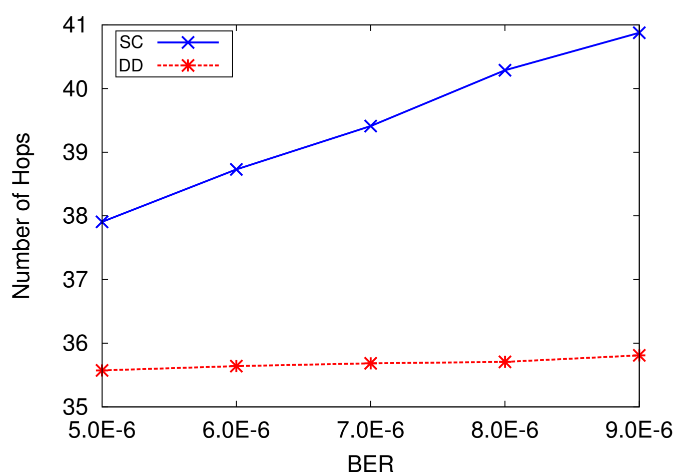


Figure 10: Number of Hops by BER

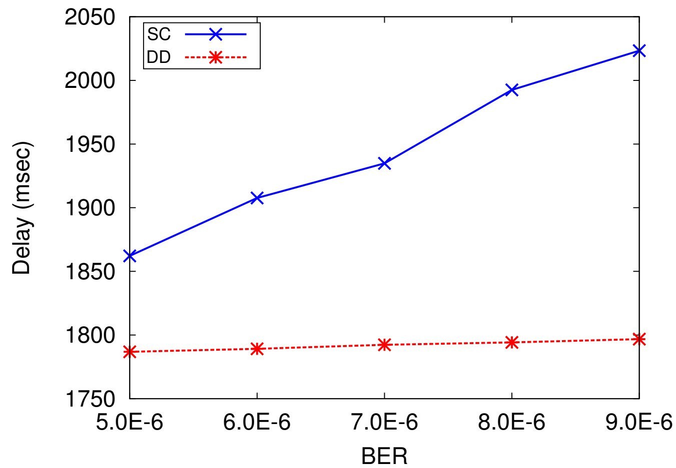


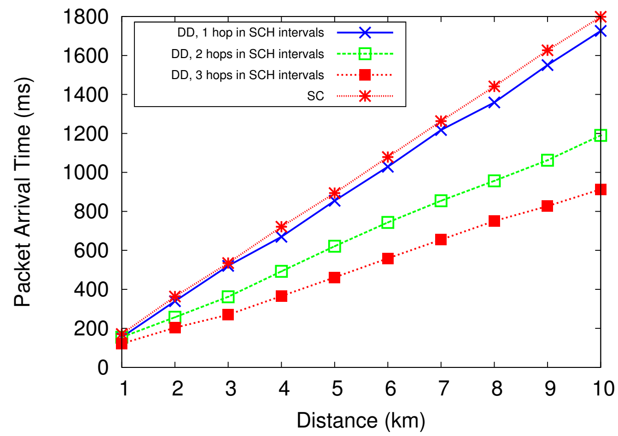
Figure 11: Delay by BER

distance and smaller number of hops, the DD method shows smaller delays reaching the target location at 10 km than the SC method.

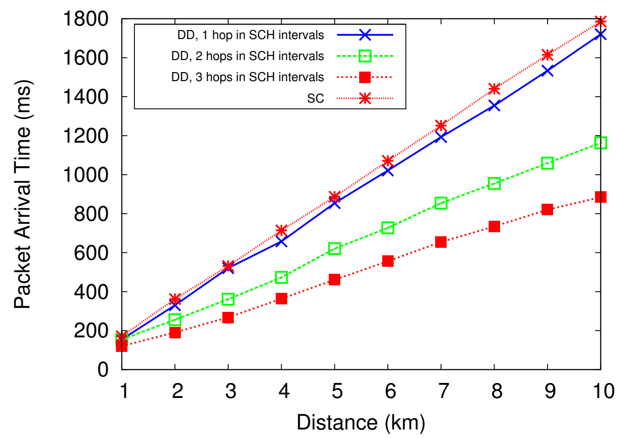
These results are important and demonstrate the DD method brings better performance than the conventional single channel method even without using the multi-hop delivery in SCH intervals, which is the main strength of the DD method. Considering the varying characteristics of wireless channel in VANETs, the strong aspect of the DD method in low BER situation becomes critical.

Next, the case when multi-hop delivery is used in SCH intervals is simulated.

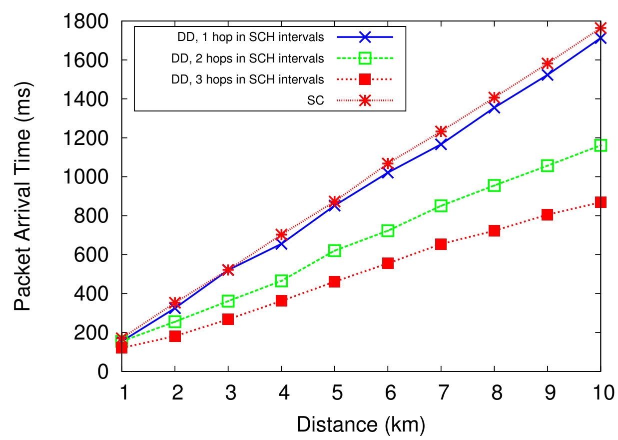
While the SC method cannot use multi-hop in a service channel, the DD method can use the multi-hop in SCH channels. Figure 12 shows the effect of multi-hop forwarding in the service channel. The number of hops increases from one to three. As mentioned in Section 3.2.2, the maximum number of hops in a channel is equal to the number of available channels, which is six in the current VANETs specification. However, in this thesis, the possible maximum number of hops is limited to three. If the number of hops becomes six, it will use most of the available bandwidth in the SCH intervals. Then, all other traffic through the SCH channels will be congested. In the simulation, the maximum number of hops is set to the half of the possible maximum number, which is three. Figure 12 shows the reduced end-to-end delay as the number of multi-hop varies in each channel.



(a) Packet Arrival Time with Vehicle Density 190 per km



(b) Packet Arrival Time with Vehicle Density 240 per km



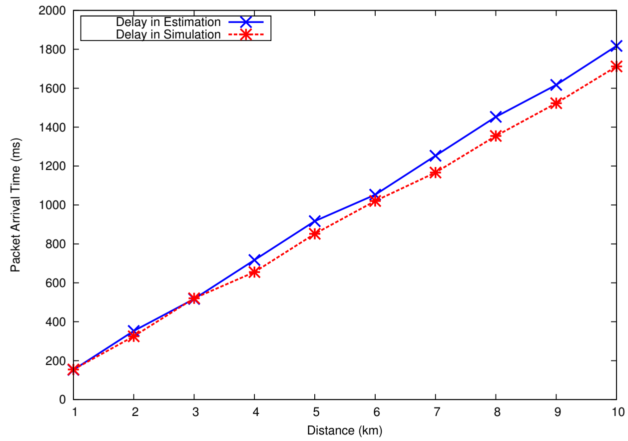
(c) Packet Arrival Time with Vehicle Density 290 per km

Figure 12: Packet Arrival Times with Multi-Hop in SCH Intervals

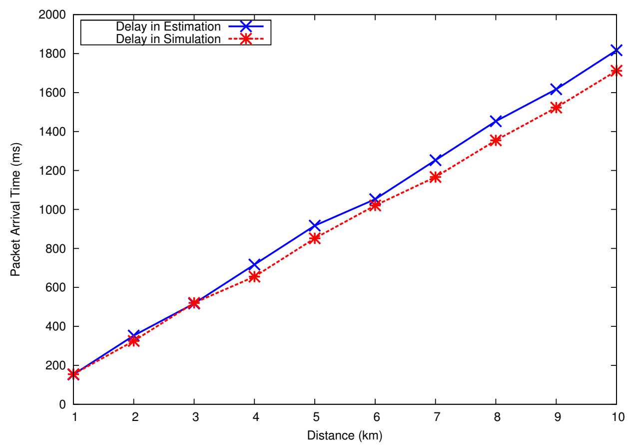
Figure 13 compares the measured delay with the analytical results from equation (5), while varying the number of hops from one to three. Figure 13 confirms that the analytical results match the measured delay in simulation.

3.4 Conclusion

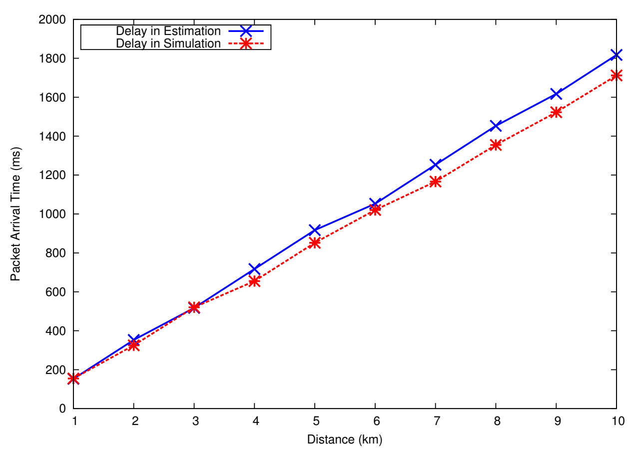
While VANETs support multiple channels, the mixed structure of CCH intervals and SCH intervals is not efficient to deliver a large amount of information quickly since only one channel exists in CCH intervals. To reduce the excessive usage of the control channel, *divide-and-deliver* has been introduced in this research. The *divide-and-deliver* method provides a way to use multiple channels efficiently. The multiple deliveries in SCH intervals that is not available to the conventional single channel method help deliver a large amount of safety information quickly. Also, the reduced number of packets that each vehicle receives makes *divide-and-deliver* more reliable in low BER environments. Considering moving vehicles that experience various status of wireless channel, this reliable feature of *divide-and-deliver* becomes more important. In a lower BER environment, *divide-and-deliver* can forward packets with longer one-hop distances. This longer one-hop distance reduces the delay to the target location and consequently enables the proposed *divide-and-deliver* algorithm to be an effective tool to deliver safety information while utilizing multiple channels in VANETs.



(a) Packet Delay Analysis with one hop in SCH intervals



(b) Packet Delay Analysis with one hop in SCH intervals



(c) Packet Delay Analysis with one hop in SCH intervals

Figure 13: Packet Arrival Times Analysis

CHAPTER 4

SAFETY MESSAGE FORWARDING IN MULTI-CHANNEL IN LOW DENSITY VANETS

4.1 Introduction

In the previous chapter, the *divide-and-deliver* method, which *divides* the entire multimedia safety information by the number of available SCHs and *delivers* the divided packets in each SCH, was introduced. With this method, the amount of bandwidth used in each channel for delivering multimedia messages can be minimized. Then, vehicles in each channel can forward the divided small packets to the other vehicles via multi-hop. That multi-hop delivery in SCH intervals is not available in the single channel method that uses only one channel in both CCH and SCH intervals. With the multi-hop forwarding, the *divide-and-deliver* scheme can deliver multimedia messages quickly to the target vehicle or infrastructure with fewer CCH intervals. Moreover, the *divide-and-deliver* method has better performance in lower bit-error rate (BER) environments since it sends a smaller number of packets in each channel. This makes a longer one-hop distance and a shorter end-to-end delay. These are good characteristics when delivering a large amount of information such as multimedia.

However, there is a unique challenge in realizing the divide-and-deliver scheme in a multi-channel VANET environment. The specific challenge is low reliability due to low connectivity between vehicles. The distributed vehicles over multi-channel decrease the density of vehicles in every channel. In some cases, there may be channels where no vehicles exist within a radio range of a vehicle. Since the *divide-and-deliver* method divide information over all the channels, if some information fails to be delivered in some channels, the original information cannot be gathered at the end point. While there are many other factors that lower reliability such as wireless channel, mobility and obstacles, the effect of these physical layer factors does not change from single channel to multi-channel.

Indeed, this low density or low connectivity is critical to the packet relay.

Therefore, in this chapter, an enhanced version of the *divide-and-deliver* method utilizing *network coding* is introduced for addressing this low density problems. With network coding, this enhanced scheme achieves efficient and reliable communication between vehicles utilizing multiple channels while reducing the amount of bandwidth borrowed. The enhancement is achieved through two steps. At the first step, the enhancement is focused on improving the reliability of low vehicle density environments. While this enhancement improves the reliability considerably, one drawback is an extra delay for a packet to arrive at the target point. This delay comes from gathering network coded packets in CCH intervals to decode the original information. In the second step, the extra delay has been removed by introducing multiple deliveries in the SCH intervals. These multiple deliveries are similar to the multiple deliveries in the previous chapter. Even with network coding, it still uses the small amount of bandwidth in each channel. So, there is enough bandwidth for multi-hop delivery. However, the multi-hop delivery lowers reliability compared to the single channel method. So, it requires extra packets to sustain better reliability compared to a single channel method.

The analysis of protocols, reliability, and the required bandwidth will be described in the following sections. The simulated results show that the proposed scheme reduces the delay and increases the reliability of the system compared to a scheme utilizing only the single SCH channel.

This chapter proceeds as follows: In section 4.2, the design of the proposed protocol is described. In section 4.3, the simulation results and analysis are introduced. In section 4.4, the conclusion is presented.

4.2 Protocol Design

In this section, the design of the proposed protocol is described while addressing the challenges associated with the multi-channels is introduced.

4.2.1 Low Success Rate

The *divide-and-deliver* algorithm relies on the successful delivery of packets through multiple channels. For the *divide-and-deliver* algorithm to be successful, the divided packets should be delivered successfully in all SCH channels. When the vehicle density is high enough, all packets are delivered though all SCH channels successfully. However, when the vehicle density is low, some of packets cannot be delivered though some channels.

The following simulation results show the reliability of the *divide-and-deliver* algorithm according to the various vehicle densities. For the testing, only one-hop reliability has been measured. First, vehicles are distributed over the 10 km road. The radio range is 300 m and perfect reception of a packet inside a radio range has been assumed. So, if a vehicle is inside the radio range of a source vehicle, the vehicle is supposed to receive a packet successfully. A source vehicle is randomly selected on the road and broadcasts six packets in a CCH channel. After receiving the initial broadcasts, all vehicles switch to one of the six SCH channels. The vehicles receiving all six packets successfully are called relay vehicles. After they moved to one of the SCH channels, they forward one packet in their channel. If each packet is forwarded successfully to another vehicle in each channel, this is a successful delivery. The success delivery rate is defined as the number of success delivery cases over the total number of simulation runs. The simulation results in Figure 14 show the success rate of the *divide-and-deliver* algorithm is high when the vehicle density is high. However, it shows the low success rate when the vehicle density is low.

The low success rate for the low density case is caused by two factors: 1) unoccupied channel (UC) and 2) unreached vehicle (UV). The unoccupied channel means there are channels where no relay vehicles exist. Since vehicles select the service channels randomly, there are cases where relay vehicles exist only in some of the channels, but not all of them. This is the main reason for the low success rate in the low density case.

Another reason for the low success rate is the unreached vehicle. The unreached vehicle situation occurs when there are no vehicles in the transmission range of a relay vehicle after

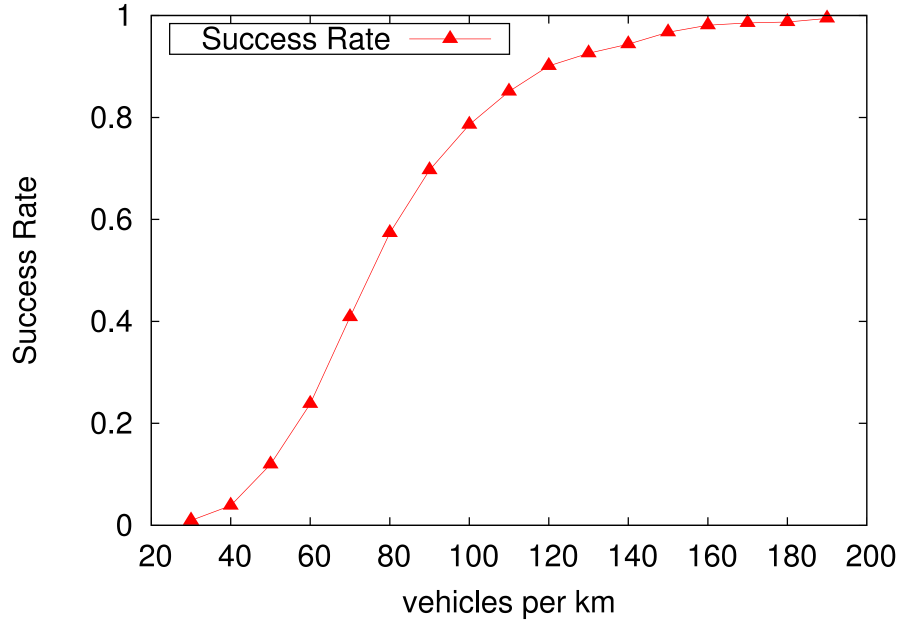


Figure 14: One-hop Success Rate

relay vehicles occupy all the six channels. The relay vehicle cannot deliver a packet in a channel.

Figure 15 shows these two failure factors while varying the vehicle densities. When the vehicle density is extremely low, the main cause of the failures is the unoccupied channel. Since there are not many vehicles to occupy all the channels, the packets cannot be delivered. The failure rate of the unoccupied vehicles decreases rapidly when the vehicle density increases. When the unoccupied vehicle decreases, the unreached vehicle becomes the main factor to fail the successful delivery in each channel.

These two factors are closely related to the number of channels. Figure 16 shows the ratio of the connectivity losses over the total number of vehicles according to the different number of channels and densities. When packets cannot be delivered due to the previous causes, this is counted as a connection loss. When the vehicles are placed in a single channel (1ch), the connectivity loss rate is low. This implies if VANETs have only one CCH channel, this low connectivity issue would not be critical. However, when the vehicles are placed in all the six channels (6ch), the connectivity loss rate increases. From Figure 16, an

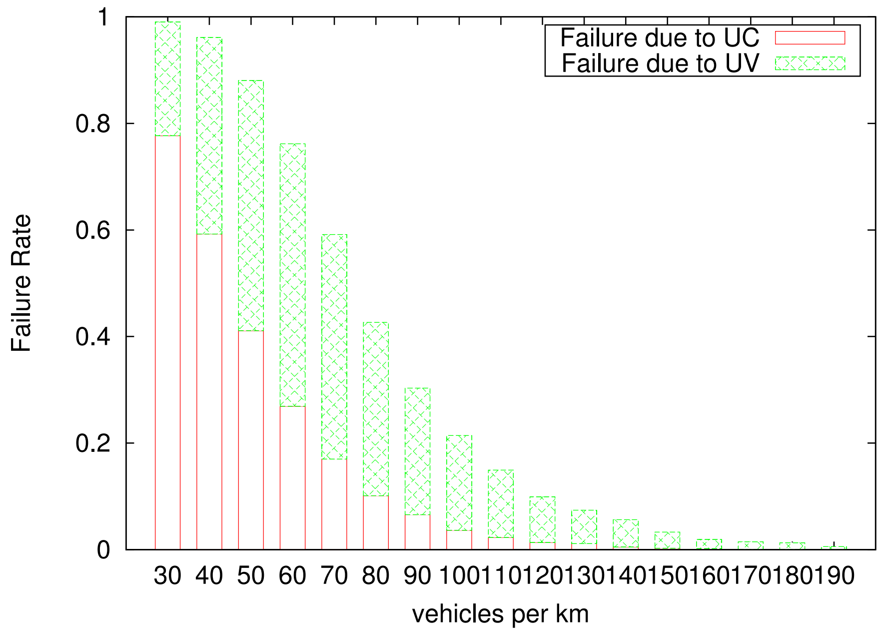


Figure 15: Causes of Failures in One-hop Delivery

interesting observation is that, even though vehicles are well connected with other vehicles in a single channel (CCH interval), vehicles start losing connectivity to neighboring vehicles in a multi-channel interval (SCH interval). This is the hidden problem of the current channel structure in VANETs. So, the *divide-and-deliver* method should address this low connectivity issue.

4.2.2 Lost Packet Compensation

After the divided packets are delivered through the SCH channels, the packets need to be collected in the next CCH interval. When some packets fail to be delivered in some channels due to the previous reasons, these packets are regarded as lost packets. The lost packets can be compensated when the same packets are delivered successfully through other channels. Then, vehicles need to know which packets will be delivered successfully and which packets will not be delivered.

However, a vehicle in a channel hardly knows which packets are lost in other channels. So, it is a difficult problem to predict the lost packet correctly. In the worst case, most of bandwidth would be wasted with the unhelpful packets that cannot compensate the lost

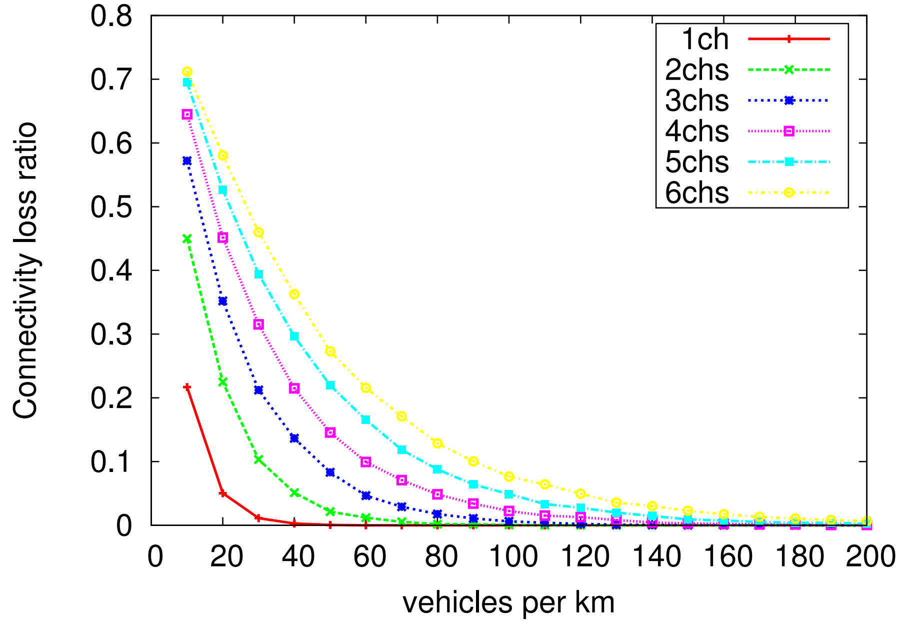


Figure 16: Loss of Connectivity

packets in other channels. To solve this packet compensation problem, network coding is a viable method.

Since the network coding enables packets to share the contents of other packets, in the case when some packets are missing, the lost information can be recovered from other packets that are received successfully. Due to this characteristic, it is possible simply to increase the number of packets in each channel without considering which packets would be dropped in other channels.

In this enhanced *divide-and-deliver*, a random linear network coding is used. The random linear network coding is commonly used in other wireless networks [73],[57]. In a random linear network coding, a sender selects coefficients randomly from Galois Field and performs a linear combination of packets and coefficients. A receiver can decode when it receives enough number of packets and pre-known coefficients. Equation (9) shows the basic operation of a random linear network coding. In network coding, a number of packets which have the same size are grouped into a segment that is called a generation. The coding is done for each generation. Assume there are n packets in a generation such as $P = [p_1, p_2, p_3, \dots p_n]$, which are plain packets before coding. To apply network coding, a sender chooses n random coding coefficients that are represented by a vector, $C_k = [c_{k1}, c_{k2}, c_{k3}, \dots c_{kn}]$ in the Galois field $GF(2^8)$. The sender generates a network coded packet according to Equation (9) in the Galois field. Then this operation is repeated with newly selected coefficients until the sender generates n coded packets such as $X = [x_1, x_2, x_3, \dots x_n]$.

$$x_k = \sum_{i=1}^{n} c_{ki} * p_i \tag{9}$$

4.2.3 Extra Network Coded Packet

Although it is possible to compensate the lost packets with generating extra packets using network coding, the natural question is how many extra packets should be added to the original number of packets.

When no extra packets are needed, the number of packets to be sent in each channel is M_{base} as in Equation (10), where R is the total number of original packets for the multimedia message and N is the number of channels.

$$M_{base} = \frac{R}{N} \tag{10}$$

When the loss of connectivity is considered, we need put more packets than M_{base}. To decide how many packets, M, are needed to be added, two factors are considered in this scenario: 1) *channel availability probability* and 2) *vehicle availability probability*. These two factors are related to the two reasons which are identified in the previous subsection. The channel availability probability is for the unoccupied channel cases while the vehicle availability probability is for the unreached vehicle cases. The channel availability probability indicates the probability of how many channels can be occupied by vehicles. The vehicle availability probability indicates the probability that vehicles exist within the transmission range of a vehicle.

To find out the channel availability probability, $\Phi^{N,Vt}(\gamma)$ is defined, which is the probability showing that vehicles occupy at least γ or more channels. $\Phi^{N,Vt}(\gamma)$ is calculated based on the number of available channels, N, and the number of vehicles, Vt. $\Phi^{N,Vt}(\gamma)$ can be described with Equation (11), where $\phi^{N,Vt}(\gamma)$ is the probability that vehicles occupy channels less than γ. $\phi^{N,Vt}(\gamma)$ can be expressed with $S^{N,Vt}(\gamma)$ and $Z^{N,Vt}$. $S^{N,Vt}(\gamma)$ is the number of cases when vehicles occupy less than γ channels. $Z^{N,Vt}$ represents all the cases when vehicles can occupy N channels.

$$\Phi^{N,Vt}(\gamma) = 1 - \phi^{N,Vt}(\gamma) = 1 - \frac{S^{N,Vt}(\gamma)}{Z^{N,Vt}} \tag{11}$$

For simplicity, $Z^{N,Vt}$ and Z^N are used interchangeably in the following expressions. Z^N also can be expressed as a set of Q_i^N, where $i = 1,...N$. The Q_i^N represents the cases when vehicles can occupy exactly i channels out of N channels, excluding cases when occupying less than i channels.

$$Z^N = \{Q_1^N, Q_2^N, \ldots, Q_{N-1}^N, Q_N^N\} \tag{12}$$

Then, $S(\gamma)^{N,Vt}$ can be expressed by adding Q_i^N where $i = 1, ...\gamma$ Since Q_1^N is the case all vehicle occupy one channel, it can be represented with Equation (13). Then, Q_2^N can be calculated using Q_1^N as given in Equation (14). Q_2^N is the case when vehicles occupying two channels out of N, excluding the cases when vehicles occupy one channel. Then, this formula can be extended to Q_N^N in (15).

$$Q_1^N = {}_1C_N * 1 \tag{13}$$

$$Q_2^N = {}_2C_N * (Z^2 - {}_1C_2 * Q_1^N) \tag{14}$$

$$Q_i^N = {}_iC_N * (Z^i - \sum_{x=1}^{i-1} {}_xC_i * Q_x^N) \tag{15}$$

With Q_i^N, Equation (11) can be expressed with Equation (16).

$$\Phi_\gamma^{N,Vt} = 1 - \frac{\sum_{i=1}^{\gamma-1} Q_i^N}{Z^{N,Vt}} \tag{16}$$

To validate $\Phi^{N,Vt}(\gamma)$, the results from Equation (11) are compared with simulation results. The simulations are done by Python scripts. The simulation scripts generate various numbers of vehicles and have the generated vehicles choose one of available channels. To simplify simulations, the number of available channels (N) is fixed to six and the number of vehicles (Vt) changes from 6 to 29. After vehicles choose channels, the scripts check if all the channels are chosen by the vehicles. If some channels are not chosen by any vehicle, this is the case of unoccupied channel (UC). In Figure 17, the simulation results show the ratio of the cases of unoccupied channels over the total simulation cases. The analysis results represent the results from Equation (11). As seen in the figure, the results from the equation match the simulation results.

For the vehicle availability probability, Ψ, a Poisson distribution model, $f(n;\lambda) = \frac{\lambda^n e^{-\lambda}}{n!}$ is used since vehicles are assumed to be distributed randomly. Equation (17) shows the vehicle availability probability using $f(n;\lambda)$, where n is zero and λ is the density of vehicles in a channel, d.

$$\Psi_d = 1 - f(n = 0; \lambda = d) = 1 - e^{-d} \tag{17}$$

Through $\Phi_\gamma^{N,Vt}$ and Ψ_{Vt}, the appropriate value of M can be computed. In next subsection, our proposed scheme to use $\Phi_\gamma^{N,Vt}$ and Ψ_{Vt} is explained.

4.2.4 Proposed Protocol

A vehicle that has multimedia safety information becomes a source vehicle to other neighboring vehicles. A source vehicle in the CCH interval transmits a number of encoded

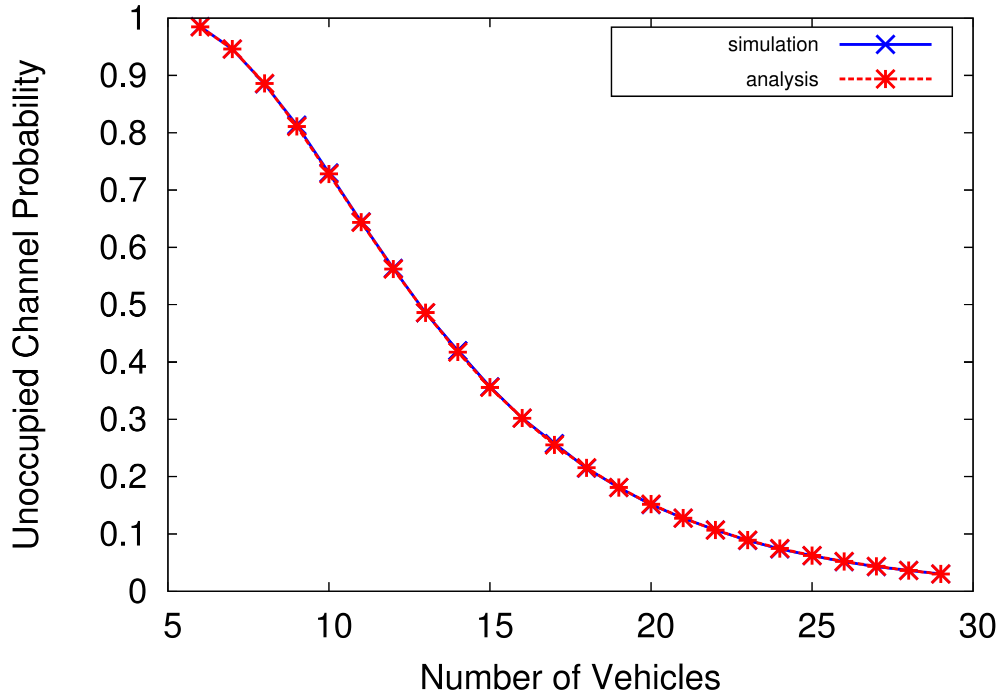


Figure 17: Validaiton of $\Phi^{N,V_t}(\gamma)$

packets with a desirable success rate, ρ. The vehicles that receive the broadcast packets successfully become relay vehicles. With ρ, the relay vehicles in the SCH interval decide how many extra packets need to be added.

To decide the number of packets to broadcast, the relay vehicles use the channel availability probability, Φ and the vehicle availability probability, Ψ with the required successful rate, ρ as given in Algorithm 1.

According to Algorithm 1, a relay vehicle increases the number of packets to be sent in each channel until it meets the required success rate, ρ. After the SCH interval ends, vehicles move to the CCH. Then, vehicles start recovering original information by gathering the coded packets that other vehicles have.

Different from the basic *divide-and-deliver*, the *enhanced divide-and-deliver* algorithm requires the decoding of network coding packets in every CCH interval. Originally network coding is designed to be effective for store-and-carry mechanism. While traditional

Algorithm 1 Finding M for the Given Success Rate, ρ

procedure FindingM(ρ)
  $R \leftarrow$total number of original packets
  $N \leftarrow$total number of channels
  $Vt \leftarrow$total number of neighboring vehicles
  $M \leftarrow \frac{R}{N}$
  $\gamma \leftarrow N$
  while $(\Phi_{\gamma}^{N,Vt} * \Psi_{\frac{Vt}{\gamma}}^{\gamma})^K < \rho$ or $M < N$ or $\gamma > 1$ **do**
    $\gamma \leftarrow \gamma - 1$
    $M \leftarrow \lceil \frac{R}{\gamma} \rceil$
  end while
  return M
end procedure

source-based coding allows only the information-source to code the information, in Network coding, each node can code its own packets. This feature gives more freedom to each node and is a very effective scheme for dynamically changing environment such as VANETs. As packets are delivered form one vehicle to the end point, the packets experience different densities and channel status. Instead of information source, the vehicle relaying the packets at each moment can decide better what kind of coding parameter is required. To change the coding parameters, first, the packet should be recovered as plain packets. That's why network coding packets need to be decoded in every CCH intervals. After getting original plain packets, each vehicle can apply the above algorithm and decide the number of network coding packets, M, at each channel.

After deciding the number of packets to be delivered, M, the vehicles in the same channel need to contend to broadcast network coding packets. To reduce the collision between vehicles in the same channel, a smart broadcasting algorithm [27] is used. With the smart broadcasting algorithm, the vehicle that is the farthest from a source vehicle can have higher priority to send packets by getting a smallest contention window size.

In the Algorithm 1, K can have different values depends on if the delivery in SCH intervals is multiple or not. When K is set to one, it is suitable to deliver packets with single hop in SCH intervals. When K is set to two or larger, it is for the multiple deliveries in SCH intervals. In next sections, the difference of K and the results according to the K will be described with more details.

4.3 Performance Evaluation

In this section, the performance of the proposed scheme has been evaluated using simulations. First, simulation environment is described. Then, the results from the simulations have been analyzed.

4.3.1 Simulation Setup

To analyze the performance of the algorithm, ns-3 simulator was used. Vehicles are placed on a 10 km road with two lanes and the same direction. The number of relayed packets is measured at every 1 km point. Packets are generated at the origin (0 km position) and relayed by vehicles until packets arrive at the end point (10 km position). The size of multimedia information is 12 Mbyte. The payload of each packet is 1 Kbyte and the transmission speed is 3 Mbps. The number of packets that a source vehicle sends in CCH interval is 12. These 12 packets can occupy more than 70% of the CCH interval when they are sent as 3 Mbps. The number of SCHs, N, is set as six. Vehicles move with average speed of 50 miles per hour and standard deviation of 5 miles per hour.

4.3.2 Results

In this section, the performance of this proposed algorithm will be analyzed in two ways: 1) $K = 1$, where a single delivery in SCH intervals and 2) $K = 2$, where multiple deliveris in SCH intervals. For each case, the performance will be investigated in three ways: 1) reliability, 2) occupied bandwidth in each channel, and 3) usage of intervals.

4.3.2.1 Single Delivery with K=1

With K=1, the Algorithm 1. becomes the following.

The reliability is the main criteria for the proposed scheme since the safety messages

Algorithm 2 Finding M for the Given Success Sate, ρ when K = 1

procedure FindingM(ρ)
  $R \leftarrow$total number of original packets
  $N \leftarrow$total number of channels
  $Vt \leftarrow$total number of neighboring vehicles
  $M \leftarrow \frac{R}{N}$
  $\gamma \leftarrow N$
  while $(\Phi_{\gamma}^{N,Vt} * \Psi_{\frac{Vt}{\gamma}}^{\gamma}) < \rho$ or $M < N$ or $\gamma > 1$ **do**
    $\gamma \leftarrow \gamma - 1$
    $M \leftarrow \lceil \frac{R}{\gamma} \rceil$
  end while
  return M
end procedure

need to be transferred to a road side unit which would be located far away and not be available immediately. To measure the reliability, the number of packets that arrive successfully at each measuring point, called packet arrival rate, is measured. For comparison, a *basic divide-and-deliver* (BDD) and a single channel (SC) method are used. The BDD method is the simple method described in the previous chapter, which divides packets by the number of channels and sends the divided amount of packets to each channel. This BDD method does not consider network coding or adding extra packets. The SC method uses only one channel in the SCH intervals. The proposed method, *enhanced divide and deliver* (EDD), has vehicles to calculate the number of packets to be sent in each channel, M according to ρ, which is specified at the beginning of simulation.

The packet arrival rate depends on both the signal-to-noise ratio (SNR) at the recipient vehicle and the number of the recipient vehicles within the communication range from a sender. Since packets are randomly dropped in wireless channels, the packet arrival rate will be a function of the number of vehicles in the range, if vehicles are under similar SNR profiles.

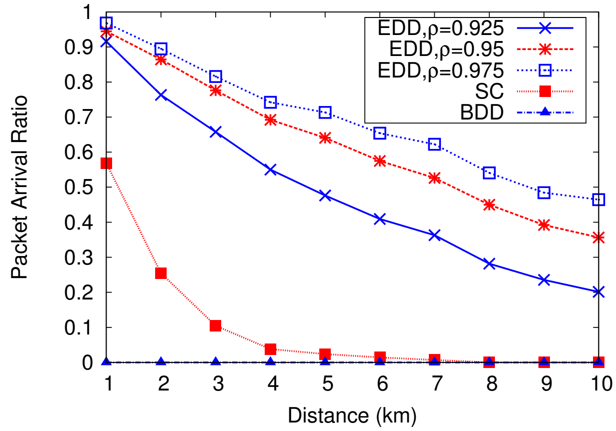
The number of vehicles has a huge impact on the packet drop rate when the safety message is transmitted by broadcasting. If a vehicle fails to receive the message due to low SNR, there will be still a chance that other vehicles receive the message successfully and deliver the message. When the number of vehicles decreases, the chance for successful reception will also be reduced and therefore the packet drop rate will increase.

Moreover, in the low density situation, there might be no vehicle existing in a radio range as shown in Figure 15. Therefore, developing algorithms that work well in this low or zero number of vehicles scenario is very important. The proposed algorithm enhances the packet arrival rate drastically by using network coding even when no vehicles receive a message in some channels.

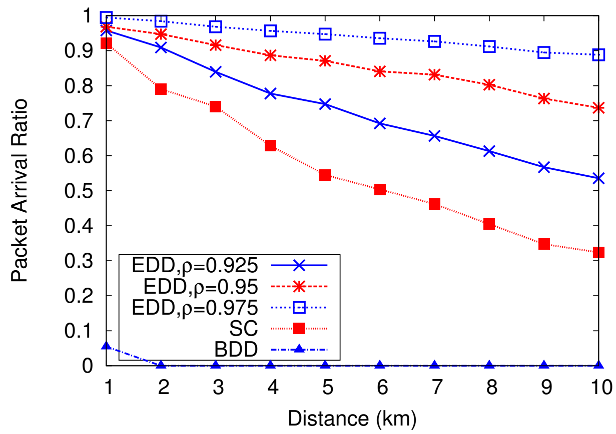
In Figure 18, the packet arrival rate at every measuring point is shown. Transferring packets in SCH intervals without considering the reduced vehicle density has a weakness in the reliability. The packet arrival rate of the BDD method is lowest out of the three methods.

In the previous chapter, the BDD method shows a good performance in delay including one-hop distance and number of hops. However, the performance in the previous chapter is based on the enough vehicle density, which at least a vehicle exists in each channel and packets are delivered successfully in each channel. When the number of vehicles is enough, the failure rate of packets can be ignored. However, in this low vehicle density case, the BDD method has a drawback.

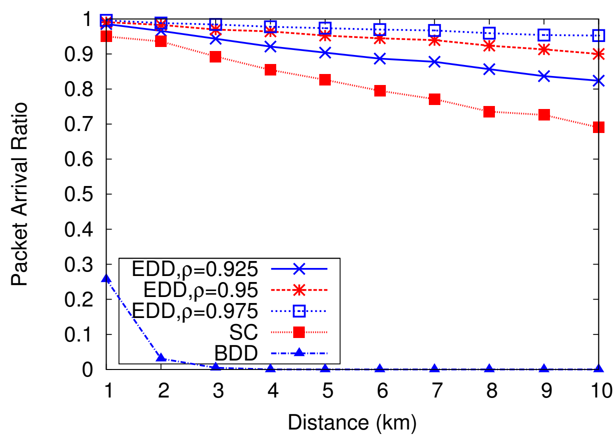
The SC method is better than the BDD method, but shows low reliability in low vehicle density simulation as shown in Figure 18a. The lack of vehicles to receive packets successfully in a selected channel is the reason for the low reliability in the SC method. On the contrary, in the EDD method, even though some packets fail to be relayed in a channel, there are packets successfully relayed in other channels. Using these surviving packets with the help of network coding, the EDD method can achieve higher reliability compared to other methods. The simulations show the EDD method is very effective in lowest vehicle density such as 18a where the reliability of the SC method is too low. The difference between the EDD method and the SC method becomes small as the vehicle density goes higher.



(a) Reliability at 30 vehicles/km



(b) Reliability at 50 vehicles/km



(c) Reliability at 70 vehicles/km

Figure 18: Packet Arrival Ratio

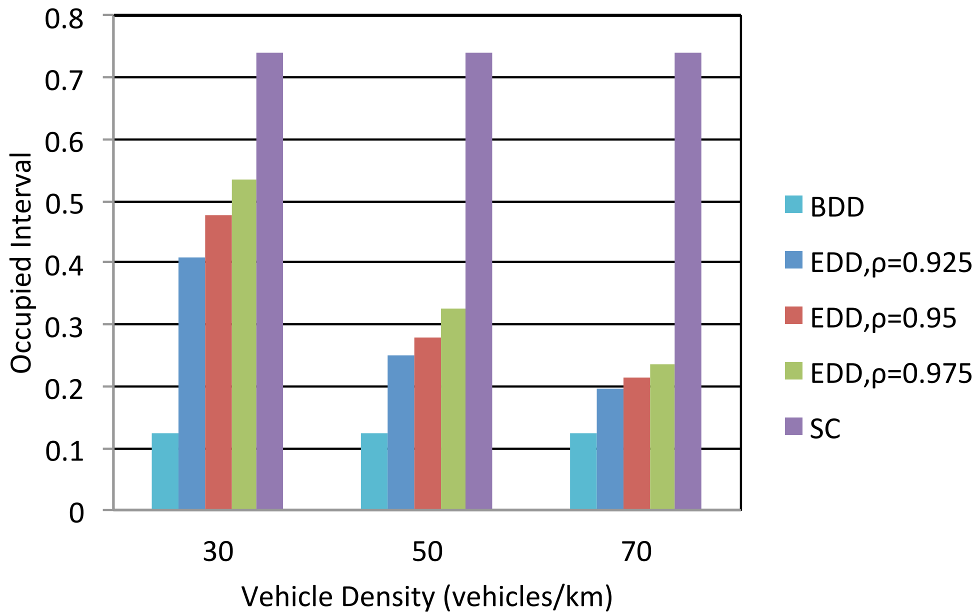


Figure 19: Used Intervals

However, the reliability of the EDD method does not come freely. It requires more bandwidth in each channel since the more packets bring higher reliability. As seen in Figure 18, the reliability of the EDD method increases as ρ increases. The higher ρ means putting more additional packets in a channel, which overcomes the loss of connectivity due to the low density.

Figure 19 shows the ratio of the time used by transferring packets in a channel to the duration of the SCH interval, which represents the usage of a channel. For the EDD method, the amount of additional packets decreases as the vehicle density increases. This decrease shows the EDD method uses the channels efficiently. Another observation is the increase of the amount of packets as ρ increases in the same density. A higher ρ makes vehicles put more packets, which increases the reliability as shown in Figure 18. While the EDD method can change the amount of packets, other methods such as SC and BDD introduce a fixed number of packets in a channel.

The BDD method uses the smallest resources in the SCH interval. However, the BDD method shows the lowest reliability as shown in Figures 18. Hence, as noted earlier, when

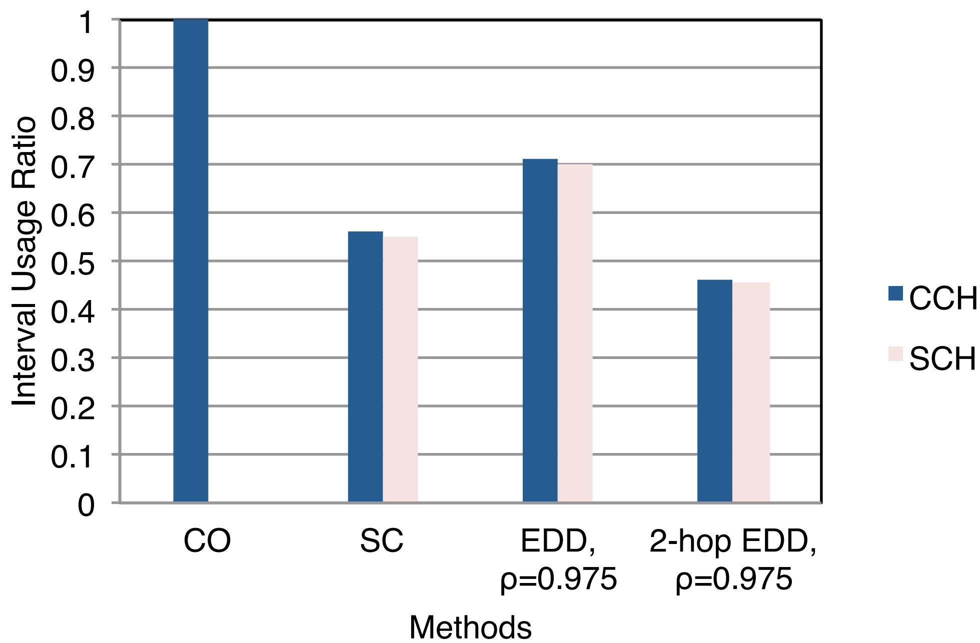


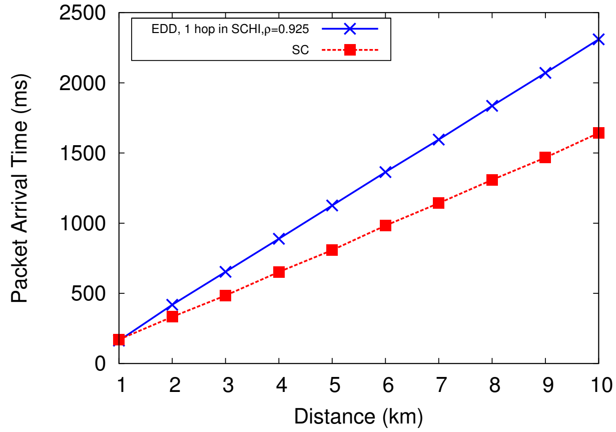
Figure 20: Channel Usage

a road side unit is far from the source vehicle, this method is not adequate.

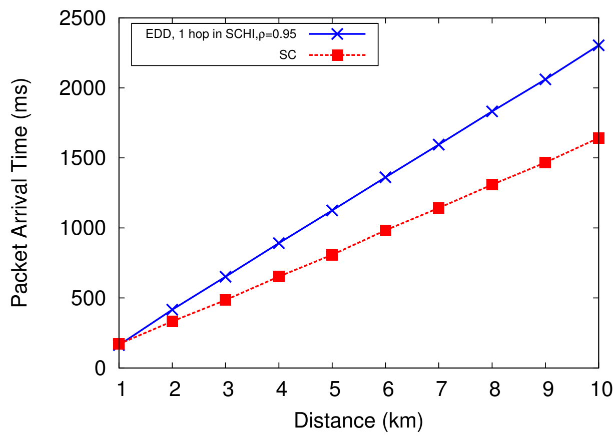
Figure 20 shows how fewer CCH intervals used for delivering traffic. As described in the introduction, the CCH interval can be congested easily by frequent short safety messages. If the large sized multimedia messages also need to be sent in the CCH interval, the congestion of a channel becomes severe and not much bandwidth would be left for other safety messages. To show the reduced usage of the CCH intervals, a CCH-interval only (CO) method is compared with our scheme as well as the single channel (SC) method. In the CO method, the packets are only sent in the CCH intervals.

Both SC and EDD methods use less CCH intervals than the CO method since they use SCH intervals. This indicates that these algorithms can provide more bandwidth in the CCH interval for other safety applications such as beacon messages than the CO method.

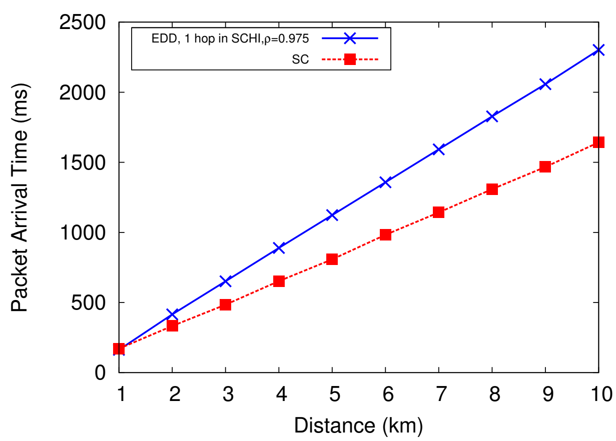
However, as seen in Figure 21, the EDD method is slower than the SC method. The reason is that the EDD method needs to share packets in the CCH intervals instead of forwarding packets to the farthest vehicle as the SC method.



(a) ρ=0.925



(b) ρ=0.95



(c) ρ=0.975

Figure 21: Packet Aarrival Time between EDD and SC at 70 Vehicles per km

A way for reducing delay in EDD is using multiple deliveries in SCH intervals as introduced in the previous chapter. Since EDD also uses a small amount of bandwidth in each SCH channel, there is enough bandwidth for multiple deliveries in SCH intervals. The following figures show the delay decrease at the vehicle density of 70 per km.

However, in the low vehicle density, the reliability can be worse if multiple deliveries would be used. Figure 23 shows the reliability when packets are delivered two times (two hops) in SCH intervals with the vehicle density as 30 per km.

As expected, when information is delivered by two hops, the reliability becomes lower than one-hop case. Moreover, the two-hop reliability is lower than the SC method. This low reliability still exists even though the vehicle density increases as Figure 25 and Figure 25.

To reduce delay without losing reliability, K value increases in the next section.

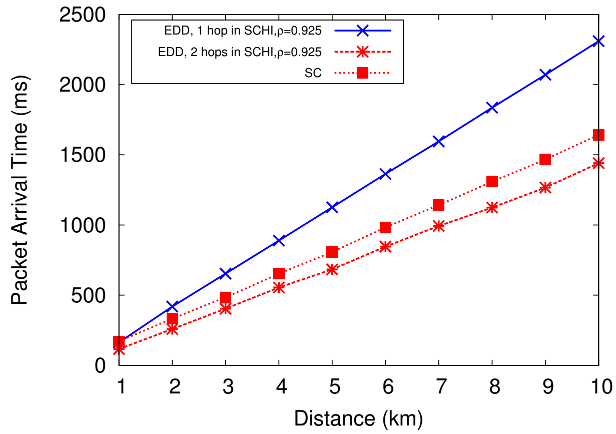
4.3.2.2 Multiple Deliveries with K=2

In the previous section, with Network coding and increased packets, the reliability has been increased compared to the SC method. However, the delay is also increased. Trying the multiple deliveries to reduce the delay has resulted in lowering reliability.

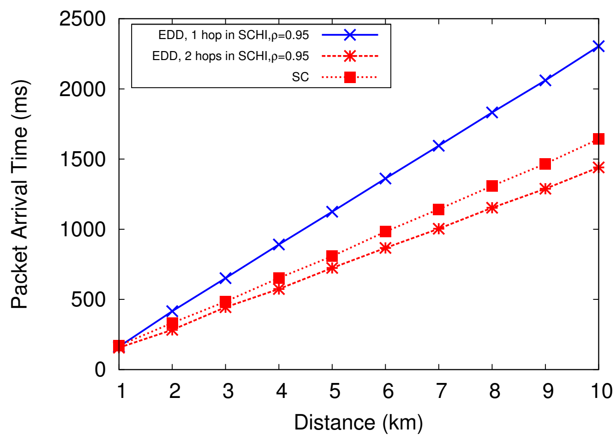
The basic idea of the EDD method is increasing the extra packets preparing the case when the packets have been lost in some channels. Instead of putting a large number of packets, the calculation based on Φ and Ψ chooses an appropriate number of packets. The previous EDD method with $K = 1$ is designed for a single delivery in SCH intervals. For the multiple deliveries, there are more chances to lose packets in each channel. Then, for compensating the increase of packet losses, the packets in each channel need to be increased with $K = 2$. Then, the algorithm becomes as shown in Algorithm 3.

The following Figure 26, Figure 27 and 28 show the reduced delay with $K = 2$ when two-hops delivery in SCH intervals by different vehicle densities. Since the multiple deliveries, the delay is reduced.

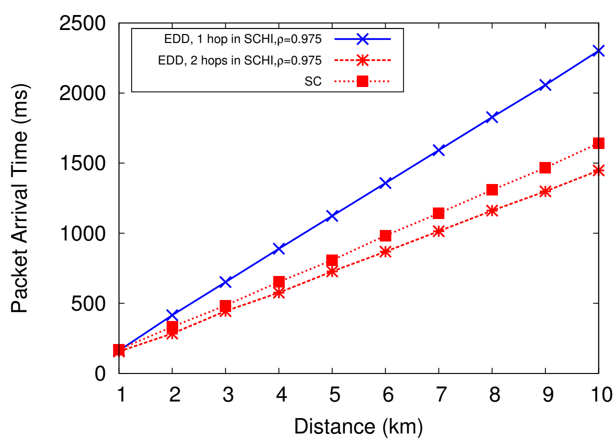
The important results from $K = 2$ is that the reliability is not lowered. As seen in Figure



(a) ρ=0.925

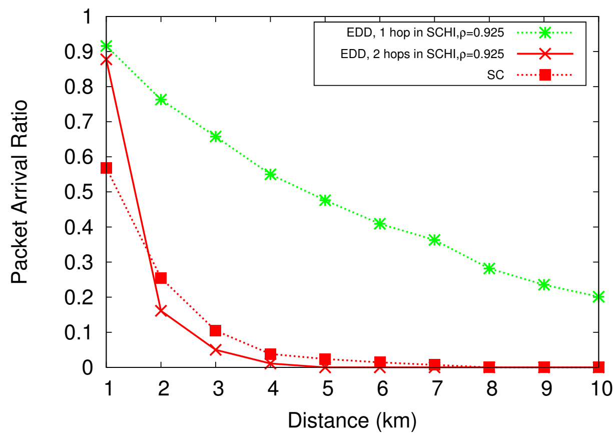


(b) ρ=0.95

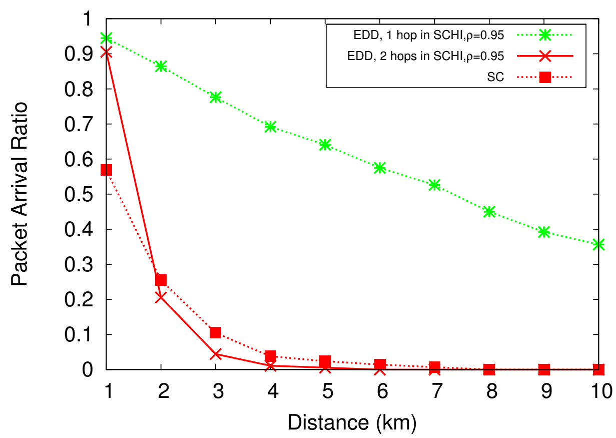


(c) ρ=0.975

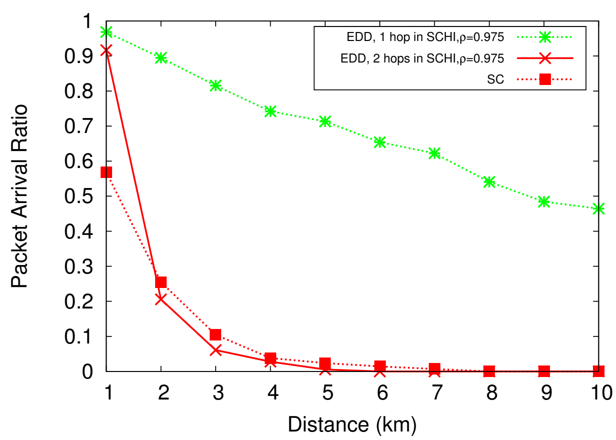
Figure 22: Packet Arrival Time with K=1, 2 hops in SCHI, Vehicle Density = 70 per km



(a) ρ=0.925

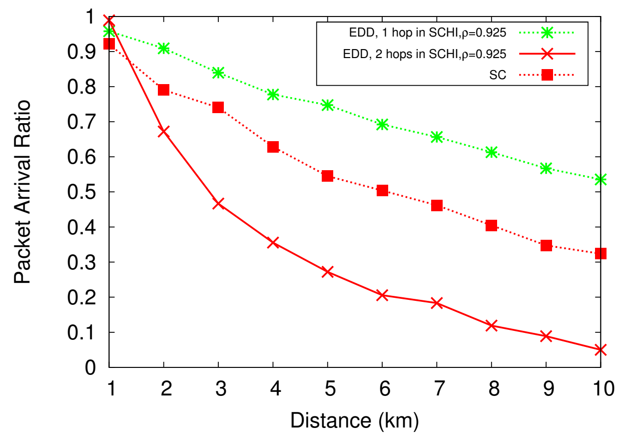


(b) ρ=0.95

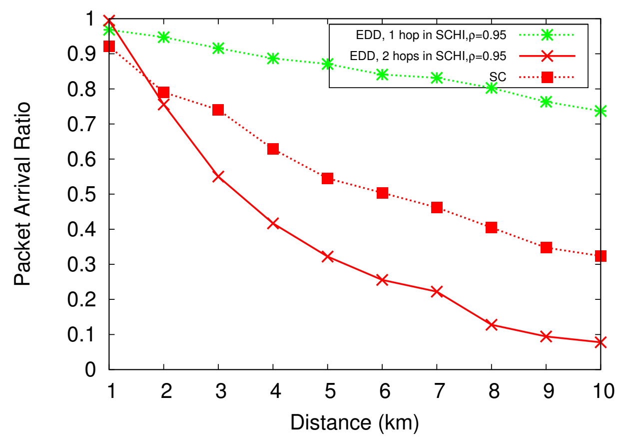


(c) ρ=0.975

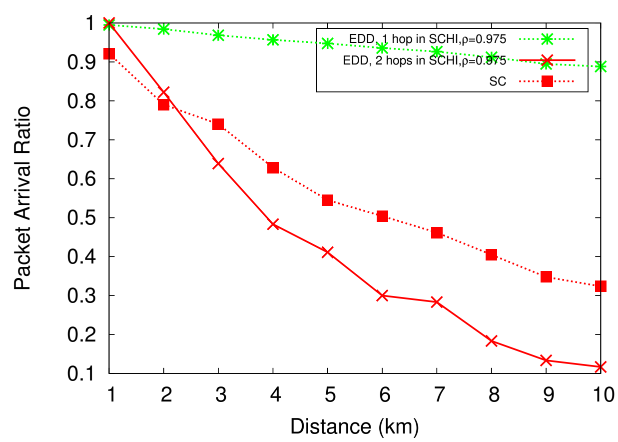
Figure 23: Packet Arrival Ratio with K=1, 2 hops in SCHI, Vehicle Density = 30 per km



(a) ρ=0.925

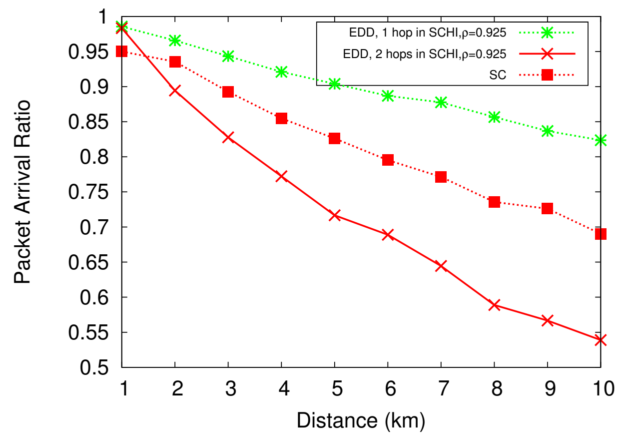


(b) ρ=0.95

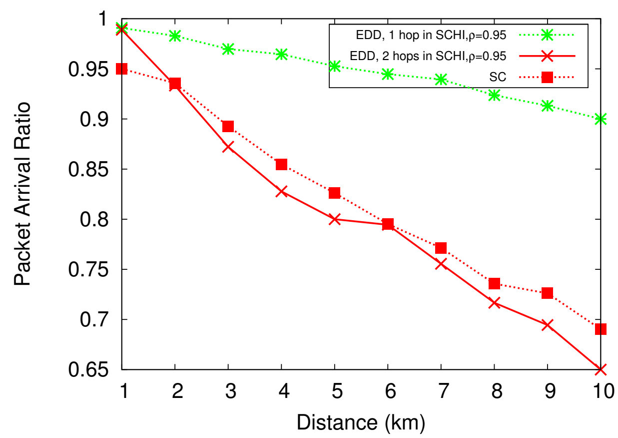


(c) ρ=0.975

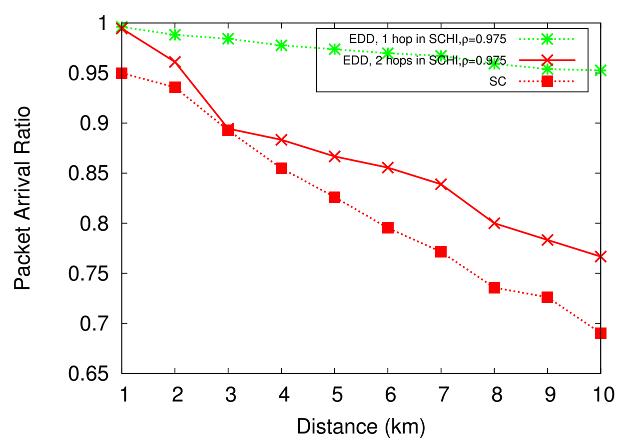
Figure 24: Packet Arrival Ratio with K=1, 2 hops in SCHI, Vehicle Density = 50 per km



(a) ρ=0.925



(b) ρ=0.95



(c) ρ=0.975

Figure 25: Packet Arrival Ratio with K=1, 2 hops in SCHI, Vehicle Density = 70 per km

Algorithm 3 Finding M for the Given Success Rate, ρ when K = 2

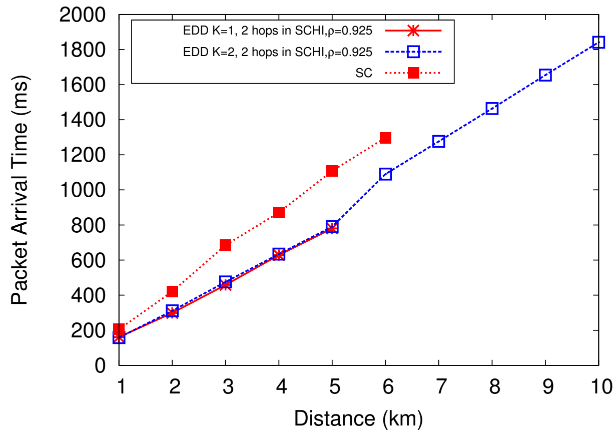
```
procedure FindingM(ρ)
    R ←total number of original packets
    N ←total number of channels
    Vt ←total number of neighboring vehicles
    M ← R/N
    γ ← N
    while ( Φ_γ^{N,Vt} * Ψ_{Vt/γ}^γ )^2 < ρ or M < N or γ > 1 do
        γ ← γ − 1
        M ← ⌈R/γ⌉
    end while
    return M
end procedure
```

29, 30 and Figure 31, the reliability is better than the SC method.

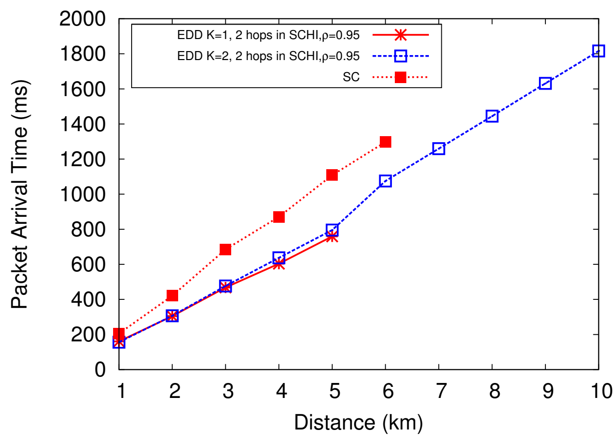
However, all of these improvements come from more packets in each channel. So, the bandwidth occupation has been increased. But the difference is very minor.

4.4 Conclusion

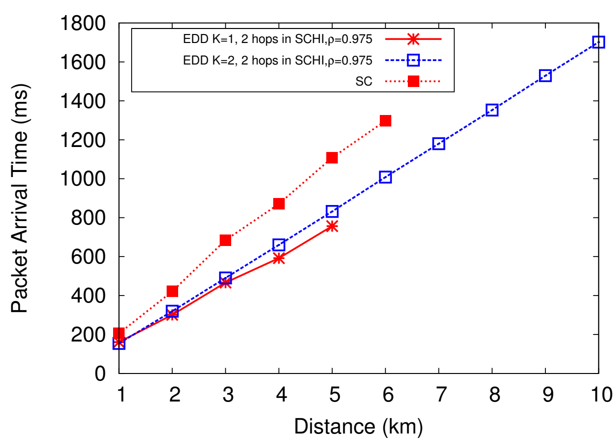
In this paper, a noble idea to deliver multimedia emergency messages in a fast and reliable fashion is presented. To avoid overloading the control channel in VANETs, multimedia contents are divided into available service channels such that the traffic load in each service channel can be minimized. However, loss of connectivity is a critical challenge if vehicle density is extremely low. To overcome this challenge, a network coding technique is incorporated with a channel survival concept to increase reliability while reducing the borrowed bandwidth from the service channels. Solid analytical derivation and extensive simulation results show the proposed algorithm significantly enhances reliability while minimizing the consumption of borrowed bandwidth compared to the single-channel scenario.



(a) ρ=0.925

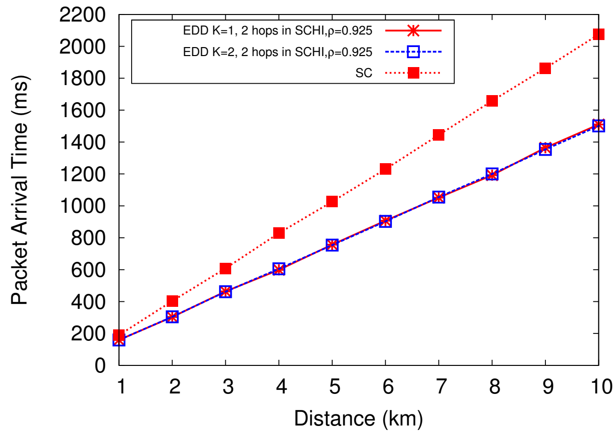


(b) ρ=0.95

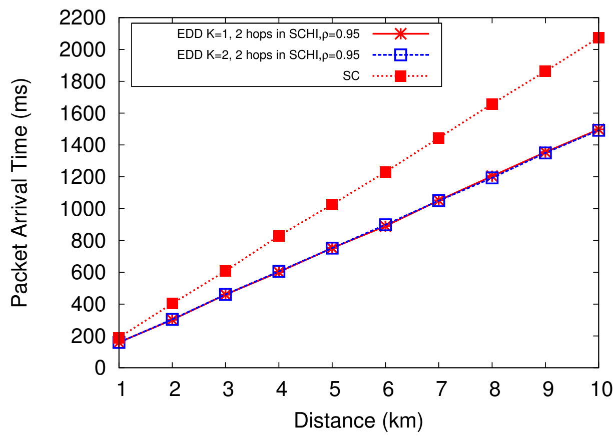


(c) ρ=0.975

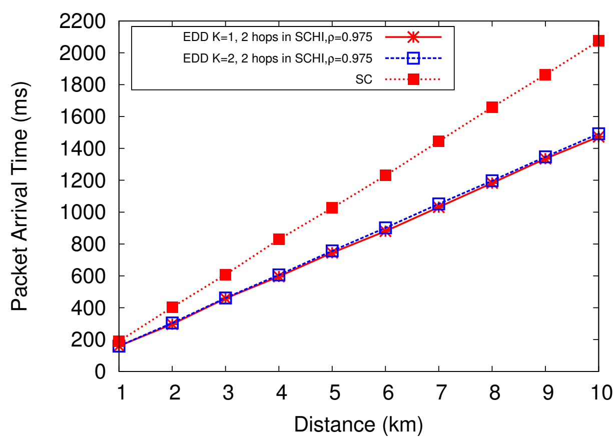
Figure 26: Packet Arrival Time with K=2, 2 Hops in SCHI, Vehicle Density = 30 per km



(a) ρ=0.925

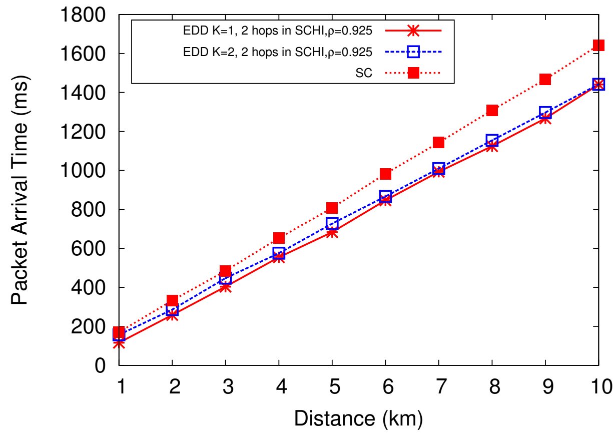


(b) ρ=0.95

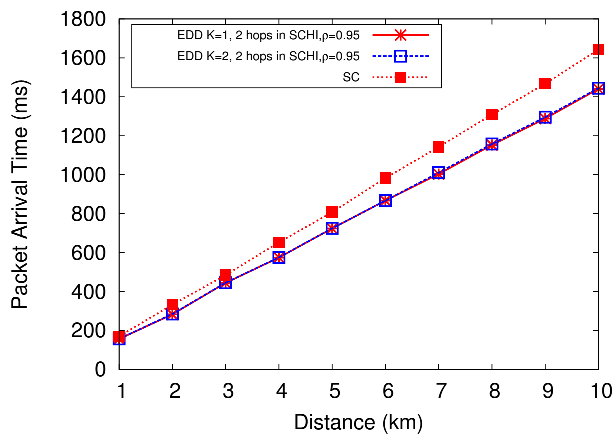


(c) ρ=0.975

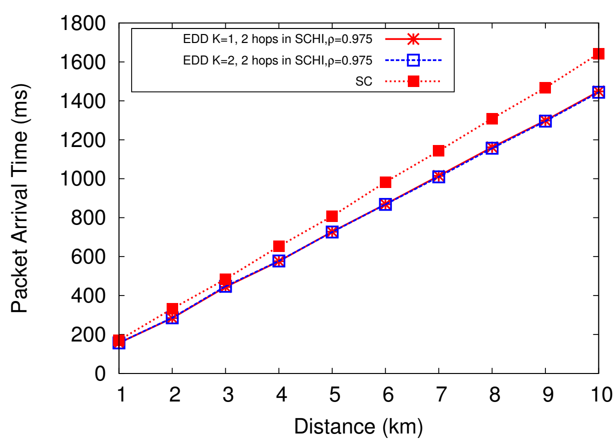
Figure 27: Packet Arrival Time with K=2, 2 Hops in SCHI, Vehicle Density = 50 per km



(a) ρ=0.925

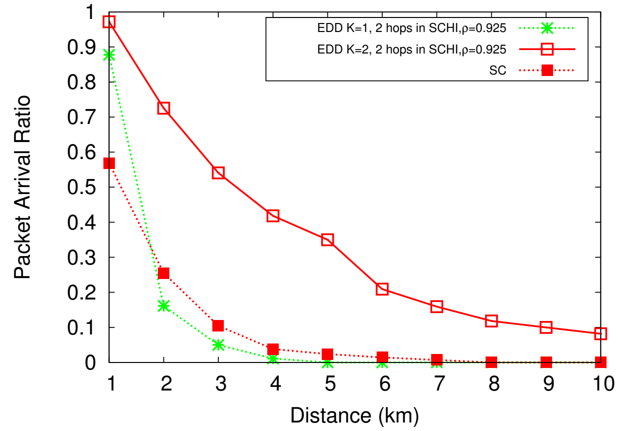


(b) ρ=0.95

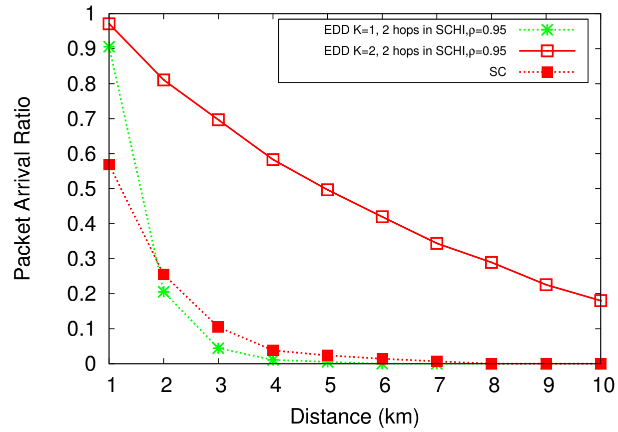


(c) ρ=0.975

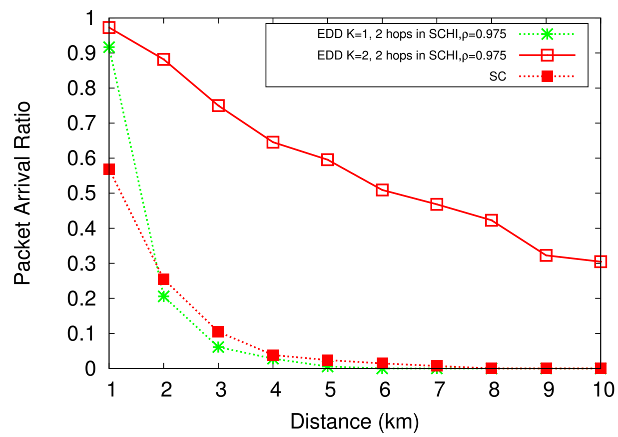
Figure 28: Packet Arrival Time with K=2, 2 Hops in SCHI, Vehicle Density = 70 per km



(a) ρ=0.925

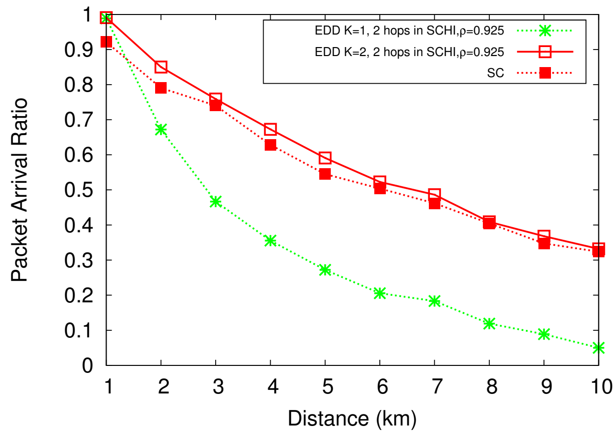


(b) ρ=0.95

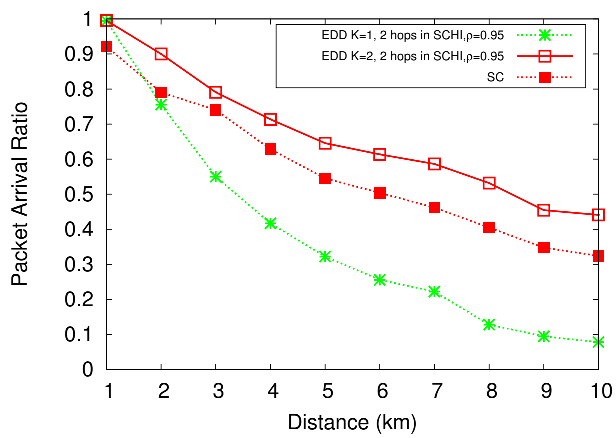


(c) ρ=0.975

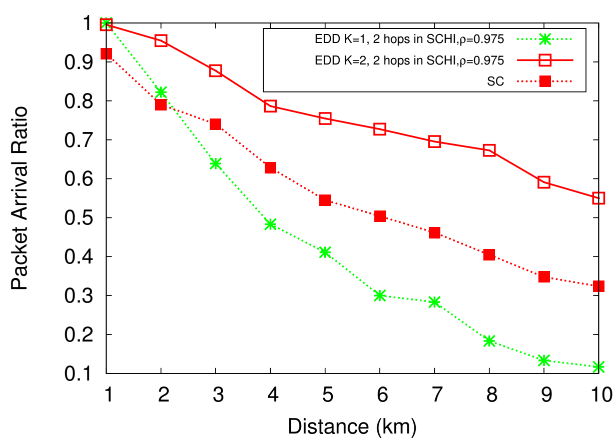
Figure 29: Packet Arrival Ratio with K=2, 2 Hops in SCHI, Vehicle Density = 30 per km



(a) ρ=0.925

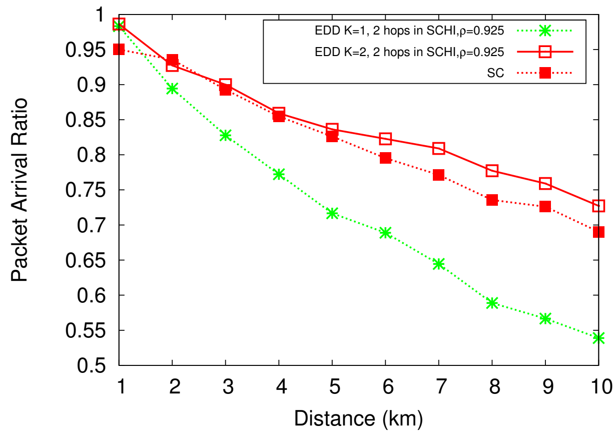


(b) ρ=0.95

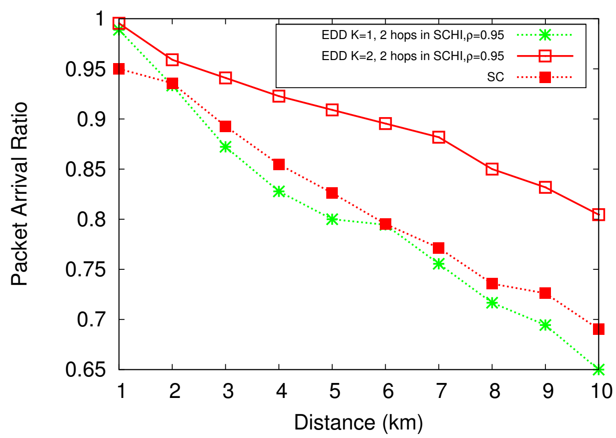


(c) ρ=0.975

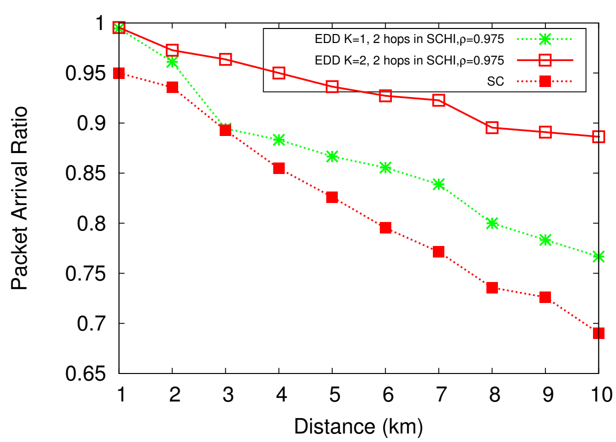
Figure 30: Packet Arrival Ratio with K=2, 2 Hops in SCHI, Vehicle Density = 50 per km



(a) ρ=0.925

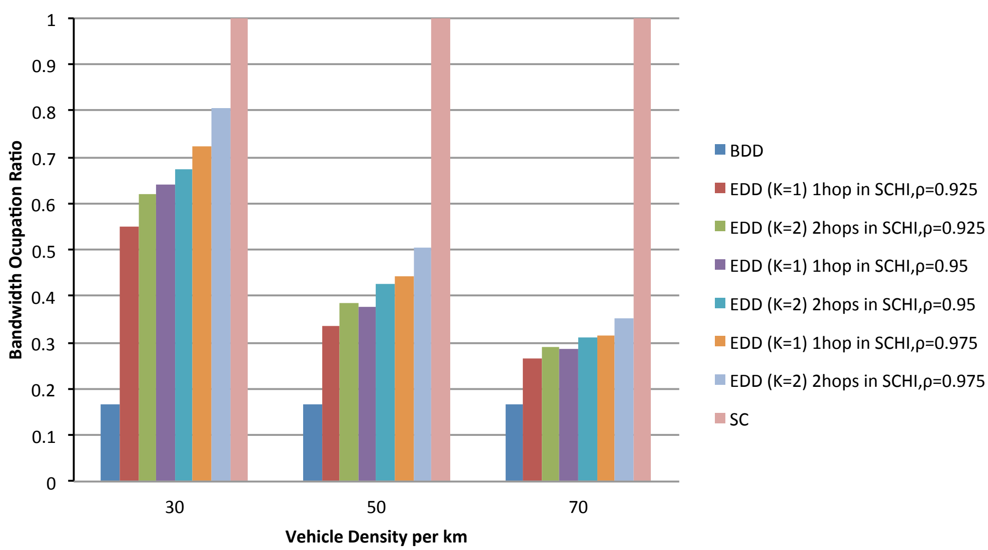


(b) ρ=0.95



(c) ρ=0.975

Figure 31: Packet Arrival Ratio with K=2, 2 Hops in SCHI, Vehicle Density = 70 per km



(a) Occupied bandwidth

Figure 32: Bandwidth Usage

CHAPTER 5

FAST BROADCAST AT THE INTERSECTIONS

5.1 Introduction

VANETs are networks of connected vehicles. Different from other network protocols, there are situations for considering VANET-specific problems. The intersection is one of these situations.

In VANETs, a safety message is delivered to neighboring vehicles that are within a one-hop distance by broadcasts. Every vehicle that receives this broadcast tries to rebroadcast to forward the message to their neighboring vehicles. This broadcast and rebroadcast is a way of spreading information from a vehicle to multiple vehicles that are far from several miles. However, these successive broadcasts bring a huge amount of network load and performance degradation, such as delay and packet drops due to collisions. This problem is known as a broadcast storm problem as shown [25]. Researchers have been working to solve this problem by letting only selected vehicles rebroadcast, and thus minimize the probability of a collision. So the best result would be to have only one vehicle be selected as a rebroadcast vehicle.

However, this approach is not desirable in a real road situation such as of an intersection. Figure 33 is already introduced in Chapter II and appears again to emphasize the importance of the intersection case. The safety message is generated from vehicle A, which is in the traffic accident. This message should be forwarded to near vehicles. If only one vehicle is selected (vehicle B), this safety message cannot be forwarded in the direction where vehicle D exists. So, vehicle E behind vehicle D would come to the accident point without hearing a warning message.

In connected vehicle projects, intersection collisions have been an important topic and there is much research about avoiding collisions at the intersections [74][75][76]. According to [77], 30% of vehicle accidents happen at an intersection. In [78], it is reported that

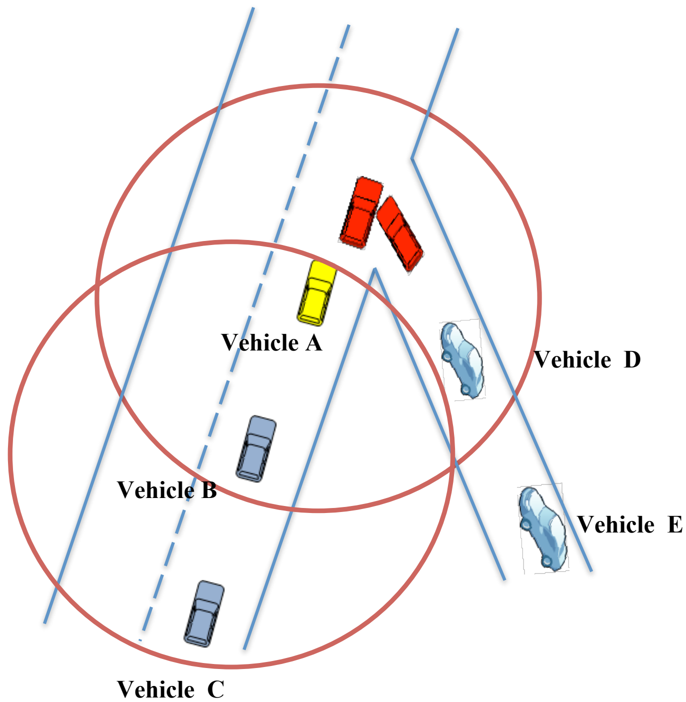


Figure 33: An Intersection Example

26% of fatalities from light vehicle crashes come from side impacts.

These statistics shows the importance of collision avoidance at the intersection. However, there is little research regarding forwarding safety messages through these intersections. Even though some papers [29],[79],[80] have addressed this problem, most their methods try to solve the collision problem, but they do not take delay into account. Since a safety message includes urgent information, it is better to deliver the message with a short delay. In [29], they broadcast a message in all directions but one direction at a time. This adds delay in covering all the directions. This comes from the fact that only one vehicle is selected from each direction. To alleviate excessive delay, the selection of multiple vehicles is required. The multiple-vehicle selection, however, brings another problem, packet collisions.

For safety messages, a collision is more critical than other messages that use a unicast. In a unicast, a sender expects an ACK from a receiver and can detect a failed transaction. In a broadcast, which is used by safety messages, the sender does not expect an ACK and cannot detect a failed transaction. So when there is a collision, a sender cannot recognize it and might not retry. Then, the safety message would be lost. For this reason, a collision or a packet drop due to a collision should be avoided. To overcome a collision in a multi-vehicle selection, we suggest a new MAC protocol which defines a Multi-vehicle Select Broadcast (MSB) MAC packet that enables the selection of multiple vehicles at one time, and enables each vehicle to forward a message without a collision between the selected vehicles.

With this MSB protocol, a fast broadcast can be achieved at intersections while avoiding packet collisions between the selected rebroadcast vehicles.

5.2 The Proposed Multi-vehicle Selection Broadcast MAC Protocol

In this section, a Multi-vehicle Selection Broadcast (MSB) MAC layer packet is described. The MSB protocol is a way of avoiding collisions between rebroadcast packets while reducing any extra delay between multiple rebroadcasts. The MSB protocol needs to define a new format for the packet header. So, the new format of the MSB packet will be described. Then, the operation of vehicles based on the MSB packet will be explained.

5.2.1 MSB Packet Frame

To avoid the possible collisions between rebroadcast vehicles, a new type of packet will be decided. This packet will include the list of vehicles that are responsible for forwarding a received safety message. Only the vehicles listed in the MSB packet can join the rebroadcast contention. This selected list already removes most of the possible contentions between vehicles. While other methods are based on the decision of the receiving vehicles only, this MSB method requires a sender to decide which vehicles will join the rebroadcast contention.

To select the list of vehicles, it is assumed that the sender vehicle keeps receiving the periodic broadcasts from neighboring vehicles and makes a list of neighboring vehicles. Usually the periodic broadcasts include the position, direction and speed of the neighboring vehicle. With this information, a sender vehicle can decide which road a given neighboring

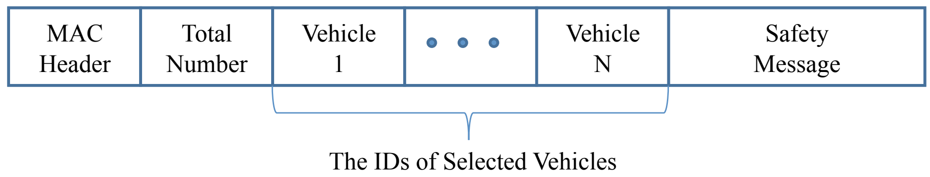


Figure 34: MSB Packet Format

vehicle is located on and the direction of the vehicle.

When a vehicle sends the periodic broadcasts, the packet header includes the identification or address of the sending vehicle. In the MSB packet, the identification (ID) of the neighboring vehicle is used to specify which vehicle will join the contention process. The packet format of an MSB packet is shown in Figure 34. A general MAC header is followed by the number of selected vehicles. After that, identifications of selected vehicles are located. The IDs of vehicles are gathered through periodic broadcasts from neighboring vehicles. The last part is a safety message to be forwarded.

5.2.2 MSB Protocol

The MSB protocol relies on the backoff operation which is the basic mechanism in IEEE 802.11p standard. Since it uses the backoff operation instead of extra packet exchanges, it can avoid the delay caused by excessive packet exchanges.

The MSB algorithm also defines a new packet as described in the previous section. However, the packet is piggy backed to the safety message as an additional header. So, it does not cause any additional packet transmission besides the transmission of the safety message. Only the increased size of the header is a redundant compared to the original safety message. If the size of a vehicle ID is the same as IEEE 802.11 MAC address that is 48 bits, the increased header size would be less than 50 bytes in most cases.

In addition, the algorithm is based on the existing operation. So, it does not need to implement separate control logic in a device. This avoid of extra logic will be helpful to implement this algorithm in real products.

The details of MSB operation is as followings. Near an intersection a sender selects multiple vehicles on each road, and generates an MSB packet with a list of selected vehicles. After hearing the MSB packet, vehicles in the list start to rebroadcast. However, these rebroadcast attempts might bring a collision. To avoid the collision from a simultaneous rebroadcast between selected vehicles, the rebroadcast sequence is controlled by a backoff counter. Even though a backoff counter is not addressed explicitly in a MSB packet, each selected vehicle has its own backoff counter implicitly. The backoff counter starts from one to the total number of selected vehicles. Let's assume there are N vehicles in a list. Then, first vehicle in a list sets the backoff counter as one. Second vehicle sets two as a backoff counter. The last vehicle sets its backoff counter as N. The difference of backoff counters is a key point of an MSB operation. Due to the difference of their backoff counters, selected vehicles can rebroadcast at a different time.

Figure 35 shows an intersection with four road segments (Road 1, Road 2, Road 3 and Road 4). Sender in Road 1 is the vehicle that has important safety information and broadcasts the initial safety message. This safety message needs to be rebroadcasted to all the directions. Three vehicles (Vehicle A, Vehicle B and Vehicle C) are selected in a MSB packet to rebroadcast the initial safety message from Vehicle A. As seen in Figure 35, these selected vehicles are the farthest vehicle from Vehicle A at each road segment.

Figure 36 illustrates the MSB operation. Sender broadcasts a safety message including three selected vehicles (A,B and C). After hearing this MSB packet, each vehicle sets its backoff counter as described above. Vehicle A sets its backoff counter to 1. Vehicle B and Vehicle C set to 2 and 3 respectively. If channel is idle, every vehicle in the list start to decrease their backoff counters. The backoff counter of Vehicle A reaches to zero while the backoff counter of Vehicle B and Vehicle C is 1 and 2 respectively. After Vehicle A rebroadcasts, remaining Vehicle B and C start to decrease their backoff counters again, which leads the backoff counter of Vehicle B to zero and start a rebroadcast. After that, Vehicle C rebroadcast. This operation can be applied to any N vehicles.

In the above operation, every vehicle in a list hears a rebroadcast of a precedent vehicle.

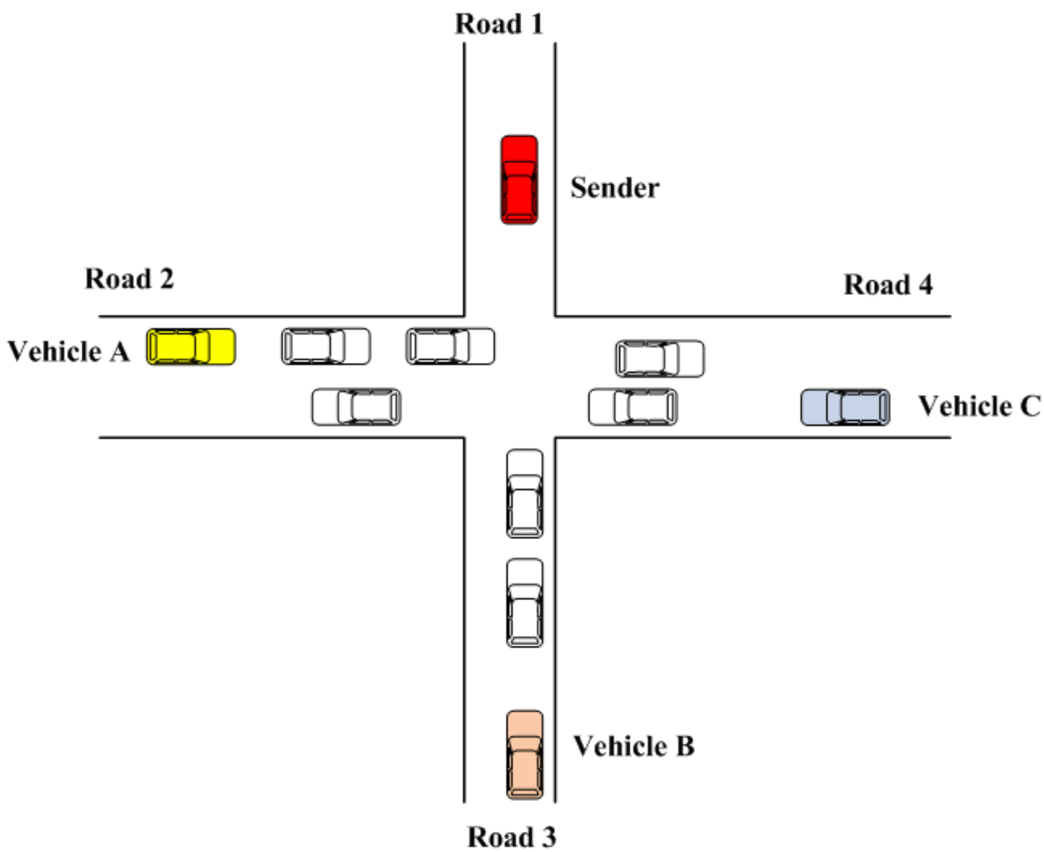


Figure 35: Vehicles at the Intersection

(Vehicle B and C hear the rebroadcast of Vehicle A). There might be another case where Vehicle B cannot hear the rebroadcast of Vehicle A. Then Vehicle B starts a rebroadcast along with Vehicle A. It seems to bring a collision. However, this collision does not make a safety message lost or prevent a safety message from being forwarded. First, if Vehicle B cannot sense a rebroadcast from Vehicle A, Vehicle B is regarded as far from Vehicle A. So vehicles that receive a rebroadcast newly from Vehicle B do not have any interference with a rebroadcast from Vehicle A. Second, some vehicles between Vehicle A and Vehicle B hear the collision. However, these vehicles already received a safety message from Sender before either Vehicle A or Vehicle B starts a rebroadcast. Therefore it is possible for a safety message to be forwarded to each direction without a collision or packet lost.

Comparing with methods [29] and [79], the MSB method has an advantage in reducing the delay to cover an intersection. In the reliable data pouring (RDP) method [79], a sender

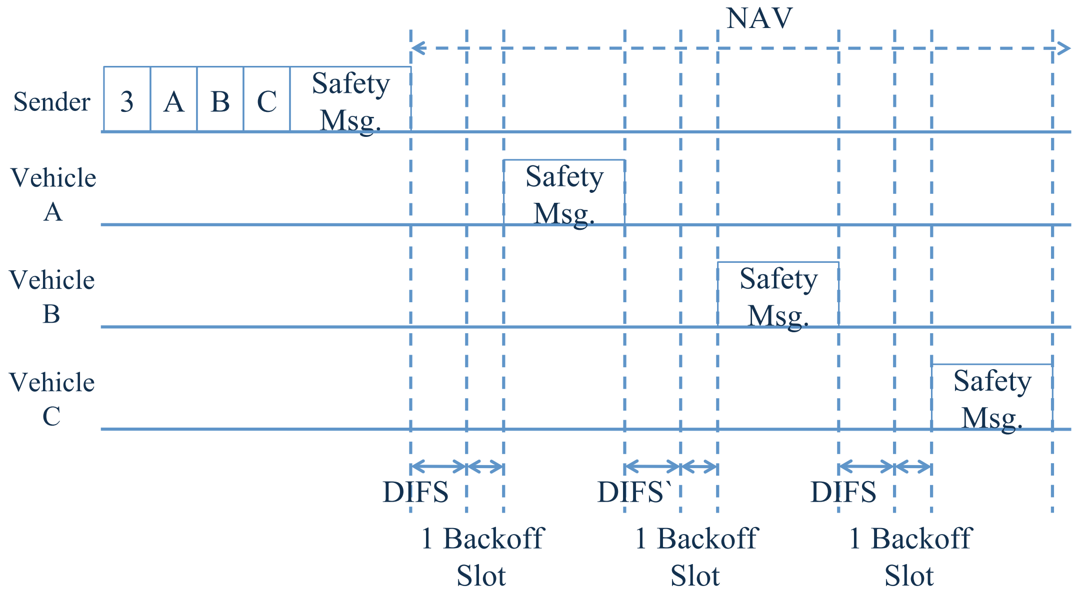


Figure 36: MSB Operation

selects a relay vehicle and waits for the relay vehicle to rebroadcast. If this is applied at an intersection, it brings more delay than the MSB method. In RDP, a sender needs to send a broadcast packet and wait for a rebroadcast packet with delay from contention window and a prespecified time period. This process is repeated to all directions at an intersection. The MSB reduces this delay since it sends a broadcast packet one time and waits for a rebroadcast packet with one backoff slot for each direction.

In addition, a Network Allocation Vector (NAV) value is added to an MSB packet to prevent other vehicles from broadcasting during an MSB protocol. Without a NAV value, a sender might suffer from extra delays due to periodic broadcasts by neighboring vehicles. A NAV value is long enough for all selected vehicles to rebroadcast and resets to zero when the last vehicle in the list rebroadcasts. Due to a NAV, a collision due to another transmission within the communication range of a sender is prevented.

Another advantage of the MSB protocol is faster rebroadcast over a wireless channel. Vehicles with high speed or behind obstacles such as big trucks might suffer from a deep fading, which results in a failure in receiving a broadcast packet. Since a broadcast packet is targeted to all vehicles, some of all vehicles are apt to fail to receive a packet correctly. For a broadcast packet, there is no other way than timer expiration to check whether a receiver receives well or not. Usually timer expiration adds extra delay. In RDP, a sender uses a timer to check if a relay node received correctly. If a timer is expired without receiving a rebroadcast, a sender re-sends a message.

In MSB, even though some receivers do not receive correctly, no time-out is required since the next-order vehicle in the MSB list starts rebroadcasting as soon as its backoff counter expires. So, instead of waiting for long timer expiration, only some backoff slots will be spent. In Figure 37, Vehicle C starts rebroadcast after two backoff slots.

Moreover, a sender can find easily whether receivers fail to receive the initial safety message. It is possible since all the rebroadcasts are ordered by the MSB list.

The sender expects all the vehicles to rebroadcast by the order in the MSB list. When a sender receives the rebroadcast from Vehicle C after Vehicle A rebroadcasts as in Figure 37, a sender can recognize immediately that Vehicle B fails to receive a initial safety message.

Also the increased backoff slots between two successive rebroadcasts let a sender to know there are vehicles that does not receive the MSB packet. This successive rebroadcast helps a sender to find failed receivers within short delay. This mechanism also reduces the entire coverage time.

At last, there is a case when rebroadcast packets create a collision even when all the vehicles follow the MSB operation correctly. In Figure 38, Vehicle C rebroadcasts its packet before the rebroadcast from Vehicle A has not been finished. This rebroadcast makes a collision and prevents other vehicles from receiving the packets from both Vehicle A and Vehicle C. However, Vehicle C follows the MSB protocol correctly. It delays its transmission based on the assigned backoff counter. The reason for this collision can be explained by the long distance between Vehicle A and Vehicle C. With reduced signal strength by the long distance, Vehicle C cannot sense the rebroadcast from Vehicle B.

Even in this case, the safety message can be forwarded to all the direction successfully. Since the packets from Vehicle A cannot reach Vehicle C, the vehicles behind Vehicle C

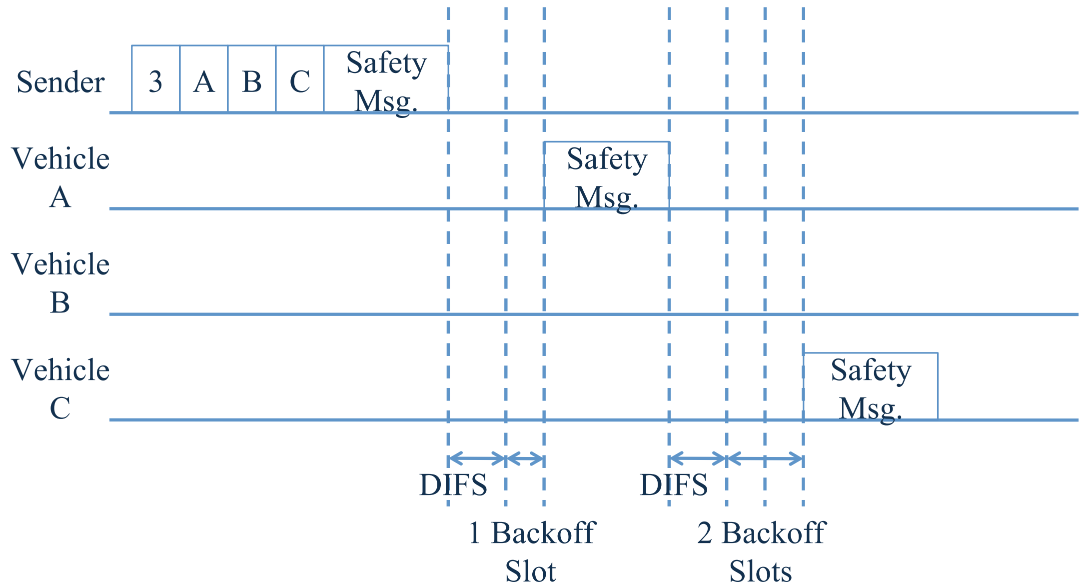


Figure 37: MSB Operation with a Failure Receiving a MSB Packet

Table 1: Simulation Parameters

Number of vehicles	5 to 45
Map Size	2000 x 2000 meters
Average Vehicle Speed	45mph
Acceleration	+/- 5mph
Number of lanes in each direction	2
Period of safety message transmission	at every 1 sec

can receive the packets from Vehicle C successfully. Even though the signal from Vehicle A arrives at the vehicles behind Vehicle C, it has a weak signal power and the strong signal power from Vehicle C can override the weak signal. So, the packet from Vehicle C can be forwarded to the Road 4. This is the same to Road 1 by Vehicle A.

Only the vehicles between Vehicle A and Vehicle C fail to receive the packets by the collision. However, this failure does not cause any loss of information since these vehicles already receive the safety message from Sender at the initial time. The collided packets become redundant information even if they receive the packets successfully.

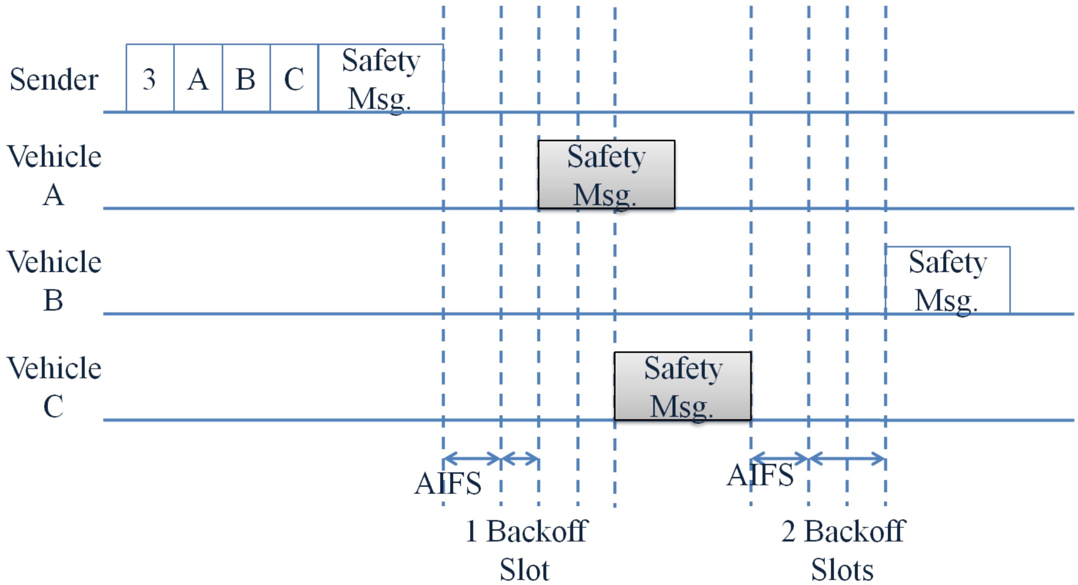
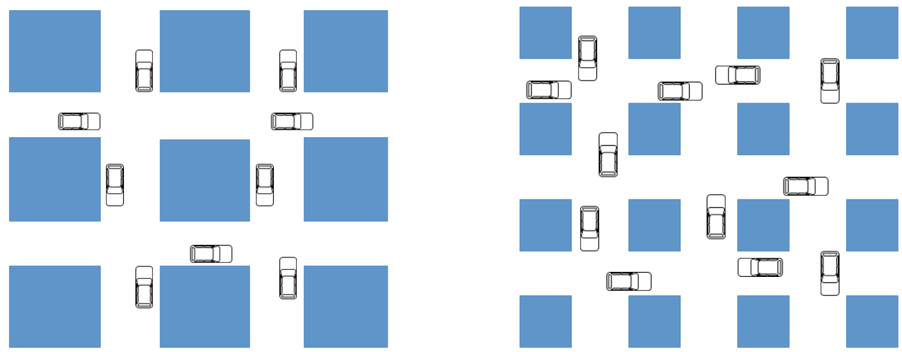


Figure 38: MSB Operation with a Collision between Rebroadcast Packets

5.3 Simulation and Results

To simulate this algorithm, NS-2 is used [81], which is a well-known simulator in the network area. Even though NS-2 supports the mobility of each node, nodes in VANET need to follow along with the road directions, not random directions. Using a USC mobility generator [82] which is a simple program to generate the mobility of vehicles under a given road plan, two virtual road maps (Map 1 and Map 2) are defined. The size of maps are 1000*m* x 1000*m* and the maps specifies road directions, width of roads, and intersections. Map 1 has four intersections and Map 2 has nine intersections. In the simulation, it is assumed that the position and direction information are known globally instead of gathering information from neighboring broadcasts. The parameters used in this simulation are summarized in Table 1.

In this simulation, the coverage and delay of the MSB protocol compared with other methods are measured. The coverage is compared between a case where multiple vehicles are selected (MSB) and a case where one vehicle is selected at intersections (OSB). To measure coverage of a safety message, one safety message is generated in every second. The duration between safety messages is long enough to guarantee a safety message reaches



(a) Map 1 (4 intersections) (b) Map 2 (9 intersections)

Figure 39: Map 1 and Map 2

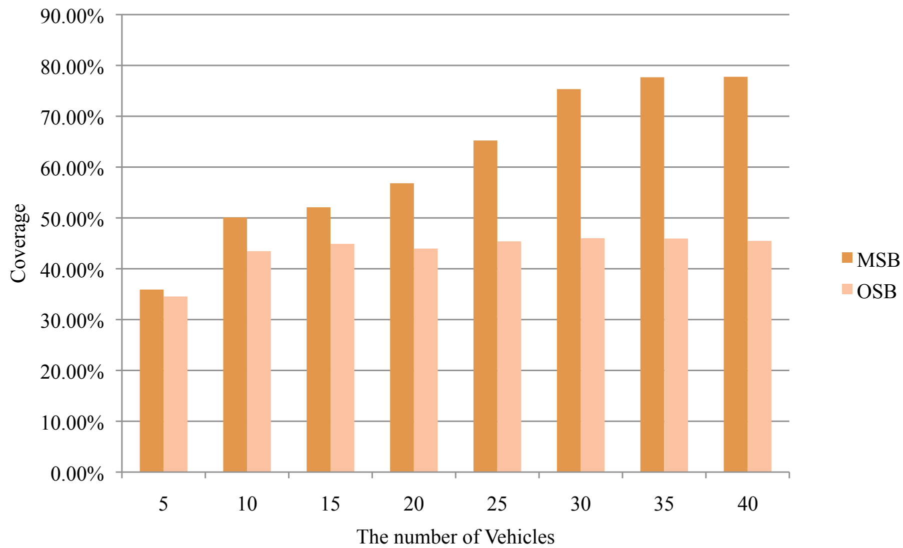


Figure 40: Coverage Results in Map 1

to the end of a given virtual road. The total simulation time depends on the number of safety messages. Each vehicle generates a safety message as many as 20 times. During the simulation the number of vehicles which receive the safety message is calculated. Covered vehicles are the vehicles that received safety messages. The coverage is defined as the covered vehicles divided by total number of vehicles.

In Fig. 40 and Fig. 41, the coverage is compared as a percentage. The MSB method has more coverage than an OSB method. The coverage of the MSB is up to 70% larger than the OSB method. The coverage is deeply related with vehicle's position. If no vehicle is at an intersection at the time a sender tries to broadcast, a message could not be disseminated

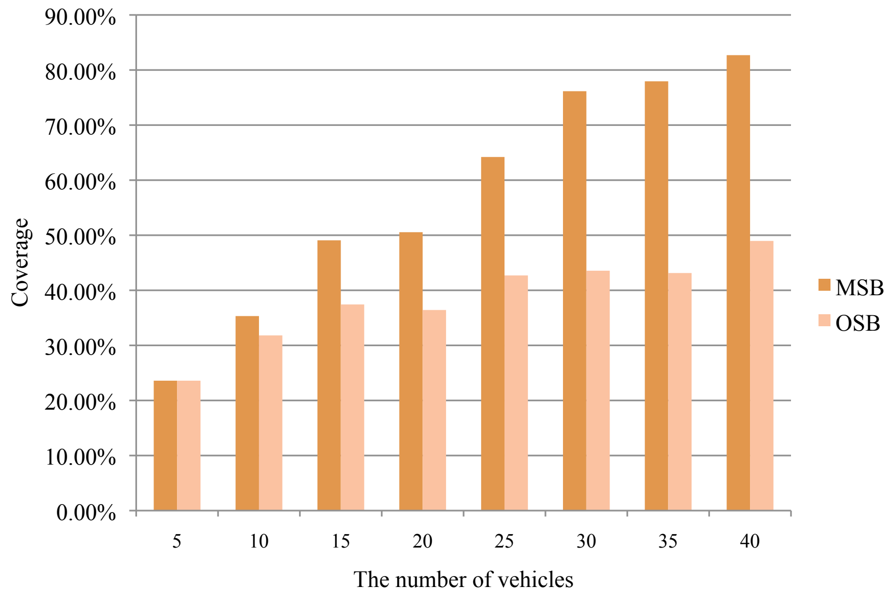


Figure 41: Coverage Results in Map 2

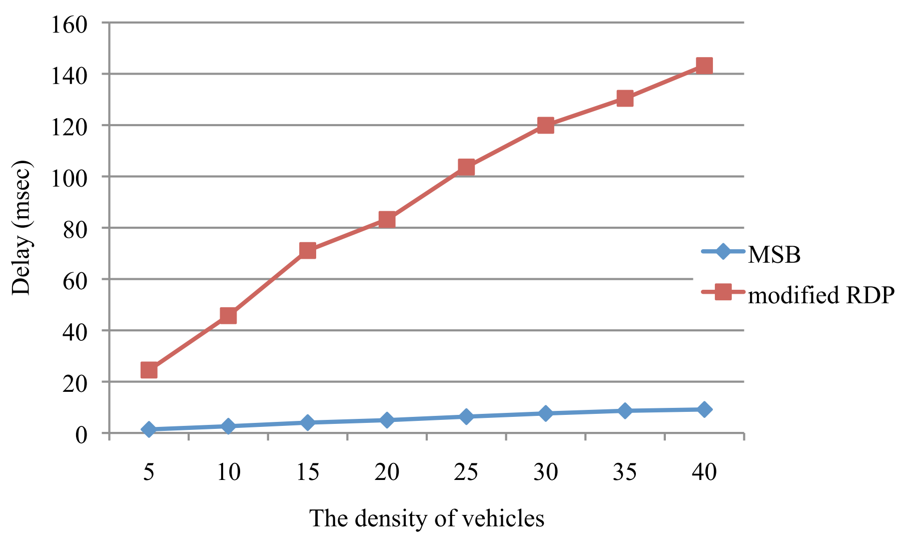


Figure 42: Delay Results in Map 1

in either case. That is the reason why the coverage increases as the density of vehicles is increased. The coverage is also not up to 100% because there is a sparse hole where no relay vehicle exists within a sender's communication range.

To compare the delay with the MSB method, a modified RDP [79] method is used. The

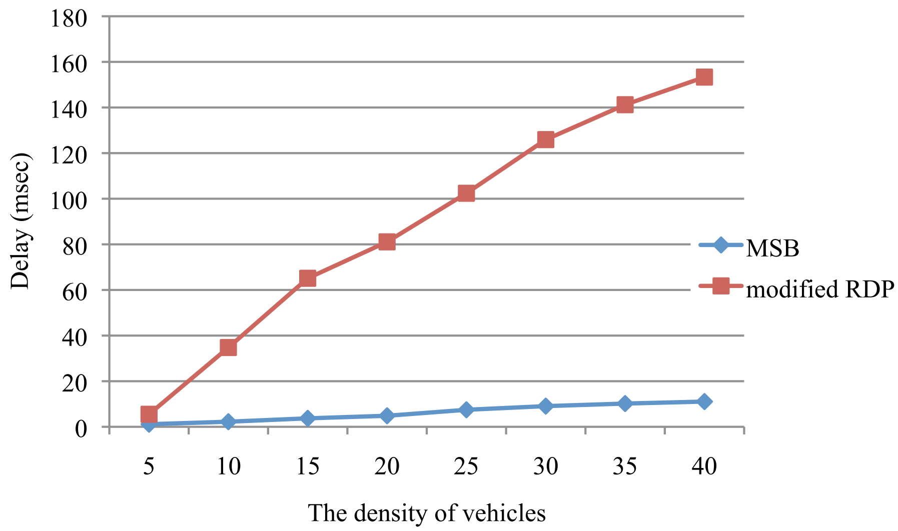


Figure 43: Delay Results in Map 2

modified RDP method enables a vehicle to broadcast for each direction at intersections without using RTS/CTS, since the original RDP method could not be applied at intersections without road side units. The delay is defined as an average time to cover all reachable vehicles.

Fig. 42 and Fig. 43 show the delay difference between the MSB and the modified RDP. In the modified RDP, the delay increases steeply as the density increases. The increased density means the probability that a safety message is passed through intersections is increased, and the delay is increased when a message goes through intersections. However, in a MSB case, the delay increase is not as much as for the modified RDP case. That is because the MSB algorithm uses fewer packets to cover an intersection. The MSB uses only one broadcast packet at each intersection, and rebroadcast packets use one backoff slot for each direction. The modified RDP algorithm consumes, for each direction, a broadcast packet, a rebroadcast packet with a delay by a contention window and timer expiration for a failed broadcast packet. The simulation shows the MSB protocol covers intersections faster than the modified RDP protocol by as much as 100 *msec*.

5.4 Conclusion

VANET, a system used for providing road safety, uses a wireless communication system equipped in each vehicle. Due to the VANET, every vehicle can send warnings of accidents to other vehicles, and forward this information to vehicles that did not hear the original warning. This safety mechanism is based on the broadcasting and rebroadcasting of a packet. However, the problem of broadcasting at intersections has not drawn much attention. In this chapter, a new MAC protocol is proposed including a new packet format, which is called Multi-vehicle Selection Broadcast (MSB), to select multiple vehicles at intersections. This MSB scheme avoids packet collisions between the selected relay vehicles using a backoff counter control. In a simulation, our scheme increases the road coverage up to 70% compared with a one-vehicle selection broadcast (OSB) scheme. Also our method decreases the coverage delay time as much as 100*msec* compared with a modified RDP method.

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

6.1 Conclusions

The purpose of this research is to provide efficient methods for disseminating safety information in VANETs. Of the many important characteristics in VANETs, the focus of this research is in two specific areas either the use of multiple channels or multiple directions.

For the multiple channels, the proposed solution in this research is dividing the large amount of safety information and delivering the divided information in multiple channels. By dividing the information, each channel can deliver only a small amount of information and this small information leaves more bandwidth for other traffic within each channel. This available bandwidth can be reused to deliver the safety information again. This extra delivery is multi-hop delivery in the channel. Since the safety information needs to be delivered in a short time, this multi-hop delivery in SCH intervals becomes an efficient solution for fast delivery. Another advantage of this *divide-and-deliver* algorithm is longer one-hops distance (shorter delay to an end device) compared to the conventional single channel method where only one channel is used. The small amount of information that each vehicle receives increases the chance of receiving packets successfully. This higher chance of successful packet receiving increases the distance of a receiving vehicle that is farther from a source.

A drawback of *divide-and-deliver* algorithm is that it requires all the cannels to deliver packets successfully. If some of packets are missing in some channels, it is hard for the end device to recover original information. So, the *divide-and-deliver* algorithm has low reliability in low vehicle density situation compared to the single channel method. To overcome this drawback, an enhanced version of *divide-and-deliver* has been proposed in this research. To increase the reliability, extra packets have been added in each channel. To avoid the necessity of finding out the specific missing packets, a network coding scheme has been introduced. With network coding, the problem of finding missing packets has been solved. Then, to decide the appropriate number of packets in each channel, a statistical model has been developed to assess the probability of channel occupation and vehicle occupation in each channel. With these two statistical models, the number of packets in each channel has been decided. With the enhanced version, the reliability has been improved over the single channel case.

For the multiple directions, the case of delivering safety information at the intersection has been investigated in this research. While most algorithms regarding disseminating safety information have focused on selecting only one vehicle that is far from the source vehicle, at the intersection, efficient broadcasts to each direction should be considered. To solve the possible collisions and reduced excessive delays between multiple packet transmissions, a new MAC layer packet has been defined. With the new packet, the vehicles at the intersection can rebroadcast the safety information with a predetermined order.

With the proposed methods in this research, the safety information can be delivered to the end point with less delay and higher reliability compared to the conventional methods.

6.2 Future Research

In this section, future research to improve proposed algorithms for Mutiple channels and Message uploading is described.

6.2.1 Multiple Channels

In chapter III and IV, an effective method to use multi-channels in SCH intervals is proposed to reduce the congestion of the common control channel, when a large amount of information needs to be delivered in VANETs. Exploiting channels in SCH intervals brings less usage of the control channels. However, it has a drawback of low reliability in the low vehicle density case. To improve the reliability, in this research, extra packets based on network coding have been proposed.

Another approach to solving the low reliability is designing a protocol to restrict the channels in SCH intervals. If only a subset of all the channels is allowed in SCH intervals, the vehicle density would not be low to cause the reliability problem. However, this approach requires a selection of a header node that will decide which channels will be used. For selecting a header node, some packet exchanges would be required, which spend more bandwidth in CCH interval. After the header node is selected, it could decide which channels would be used in SCH intervals. That decision will be based on the vehicle density. So, this method brings out two research topics: One is for the protocol to select a header node efficiently and the other is for the decision of how many channels are adequate in a given vehicle density.

Avoiding the congestion in CCH intervals is an important topic in VANETs. While above mentioned research tries to solve this problem by using channels in SCH intervals, there are situations when the CCH channel still is congested. Since all the safety beacon messages will be broadcasted in CCH, when the number of vehicles increases rapidly, CCH channel congestion cannot be avoided. One suggested way to solve CCH channel congestion in high vehicle-density situation is assigning uneven durations to CCH and SCH intervals. The current operation is assigning 100 *ms* to the sync frame which includes CCH and SCH intervals. Then, each interval has 50 *ms*, respectively. However, these evenly divided intervals are not good at handling high-demand traffic in CCH intervals. On the contrary, if the interval is changed dynamically within a sync frame based on the traffic demands, the congestion in CCH intervals can be lessened. For example, when the traffic demand for CCH intervals is high, the CCH interval has 75 *ms* while SCH interval has the remaining 25 *ms*. This increased CCH interval supports more bandwidth to increased safety traffics even in the high vehicle density situation.

However, the effect of these uneven intervals will be localized since changing intervals for all the vehicles in VANETs is not practical and not adequate. Then, a group of vehicles will be affected by the change of interval duration while some vehicles are not affected. These unaffected vehicles will exist next to the effected group of vehicles. When safety messages need to be relayed by multi-hop, this difference of CCH interval could prevent the messages from being delivered to the unaffected group of vehicles. While a vehicle in the effected group tries to deliver the messages in the increase CCH interval, the unaffected group of vehicles would already move to their unchanged SCH intervals. So, to change the intervals dynamically, the communication between the vehicles using changed intervals and the vehicles using unchanged intervals need to be solved.

6.2.2 Message Uploading

An an open topic related to this research for the future, the upload of safety message to road-side unit is an attractive topic. All the messages forwarded by multi-hop arrive at a road-side unit or an infrastructure at the last hop. At the last hop, these messages should be uploaded to the road-side unit (RSU). There are a lot of messages when messages are originated from different places. When all these messages need to be delivered to the road-side unit, the channel will get easily congested. Moreover, since vehicles do not stay for a long time in the radio coverage of a RSU, vehicles need to upload the messages quickly. In addition, while vehicles pass through the radio coverage of a RSU, usually vehicles are supposed to download a variety of content from the RSU, since the RSU is the only device connected to the Internet in VANETs. Considering all the above requirements, the channel access scheme from vehicles to the RSU should be efficient enough to make vehicles upload messages without occupying large bandwidth. So, the future research will address the problem of how vehicles can access a road-side unit efficiently.

Many studies have been conducted to increase the efficiency of the channel access [83]. These methods are called link or rate adaptation. The main goal of the link adaption is to increase the successful packet reception rate as well as reduce the amount of time that a packet occupies in the channel. These goals can be achieved partly by choosing an appropriate modulation scheme through the cross-layer design of physical (PHY) and medium access (MAC) layers. This scheme selection is based on the distance and the status of wireless channel. Using the traditional link adaptation scheme, the vehicle entering the radio range of RSU will start uploading messages with the lowest bit-rate modulation. This modulation will increase the successful reception rate but will occupy a large amount of time to finish the transmission.

This traditional link adaptation method can be improved by considering the unique characteristic of the movement of vehicles in VANETs. Different from other wireless networks, the nodes (vehicles) in VANETs move following a pre-determined route, which is a road. Then, in a certain time, vehicles are destined to pass the coverage of a RSU. While a vehicle moves through the radio coverage, the vehicle experiences different channel qualities. The quality of a wireless channel gets better as a vehicle approaches closer to the RSU. On the contrary, when a vehicle goes far from the RSU, the quality of a wireless channel becomes poor. So, if a vehicle can transmit the multimedia messages only if it is close to the physical position of the RSU, the vehicle can send a packet with the highest modulation scheme, which reduces the amount of time that a packet occupies the channel.

In the future research, a link adaptation method considering the movement of vehicles will be developed. This method allows vehicles to upload messages when vehicles are close to the position of the RSU. The expected result is the increased channel throughput and the reduced bandwidth for uploading the messages.

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