Throughput Analysis in Vehicle-to-Vehicle Networks

by

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A thesis submitted to the

School of Computing

in conformity with the requirements for

the degree of Master of Science

Queen's University

Kingston, Ontario Canada

May 2007

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Your file Votre référence
ISBN: 978-0-494-30260-6
Our file Notre référence
ISBN: 978-0-494-30260-6

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Abstract:

In recent years, providing wireless high-speed data connection service to fast moving vehicles on highways has been the focus of research in wireless technology. One approach is to use vehicle-to-vehicle multihop communication for packet relay, known as Vehicular Ad-hoc Networks (VANET). In this thesis, we propose a framework that supports high data rate connection using vehicle-to-vehicle multihop communication. We propose a generic TDMA-based MAC layer protocol, with base stations acting as coordinating points. Multihop relaying is used to connect source and destination nodes when they are out of transmission range of each other. Base stations select intermediate relay nodes for each connection, and assign channels to these nodes.

One key parameter in VANET is the network throughput, in terms of number of requests being accepted by the base station. Wireless signal interference is incurred when an antenna receives signals from various sources in the same channel. Therefore, with the limited number of channels, relays should be chosen, and channels should be assigned such that interference is avoided, and maximum number of requests is accepted. We design and implement greedy algorithms for channel assignment for two types of problems, online scheduling and offline scheduling. We identify four network parameters that affect network throughput: number of channels, transmission range, node density and request intensity. We then evaluate this algorithm against a derived theoretical average under steady network state (free flow) using different values of the network parameters. Our results show that in steady network state, the network throughput under greedy algorithm is about 70 percent of the theoretical average throughput. Offline scheduling algorithm outperforms online scheduling algorithm in all steady state test cases. Simulation results on steady network state also demonstrate that when inter-node spacing is comparable to transmission range, change of node density has significant impact on network throughput.

We also tested the greedy channel assignment algorithm using common transient states in VANET. We find out that this algorithm is resistant to slight network disturbances such as stop-and-go waves, but is seriously affected by scenarios such as gaps in the traffic flow.

ACKNOWLEDGEMENTS

I would like to thank my advisors, Dr. Selim Akl and Dr. Hossam Hassanein, for their advices, patience, and support.

I would like to thank Dr. Robert Benkoczi, for his advices and his help in proofreading the thesis.

I would also like to thank Mr. Hung Tam, PhD Candidate from the Telecommunications Research Laboratory, for the helpful discussions.

Financial support of Communications and Information Technology Ontario (CITO) is greatly appreciated.

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CALM	Continuous Air interface for Long and Medium distance
CTS	Clear to send
CSMA	Carrier Sensing Multiple Access
DCF	Distributed Coordination Function
DIFS	DCF Inter Frame Space
DSRC	Dedicated Short Range Communications
HSDPA	High Speed Downlink Packet Access for 3G
ISO	International Standardization Organization
MANET	Mobile Ad hoc Networks
PCF	Point Coordination Function
RTS	Request to send
TDMA	Time Division Multiple Access
VANET	Vehicular Ad hoc Networks
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access

CHAPTER 1

INTRODUCTION

1.1 Motivation for Vehicular Networks

Computers and wireless technology have become ubiquitous in everyday life. Whether at home or in the office, people can always communicate with each other, or connect to the internet using various types of mobile devices. A possible exception is when people are on the road. Vehicles nowadays do not have high speed internet access on highways or urban roads, nor do they have effective means to contact each other and share information. Wireless access, however, for moving vehicles is in great demand because it is a key component for applications in the following 3 fields:

1. Driving safety
2. Infotainment
3. Mobile business

For example, vehicles can exchange information with one another and warn each other of imminent collisions, or congested areas; drivers can have customized on-board radio programs when driving to or from work, children can have on-line games in backseats when traveling long distances and businessmen can share files and update information or even hold a video conference when traveling on the road. Vehicle communication is therefore an area of great potential.

1.2 Challenges

Providing wireless access to moving vehicles can be very challenging. A successful wireless technology for a vehicular environment should be able to provide *peer-to-peer connection* capability for safety related applications, and also needs to provide *high-speed connections with Quality of Service guarantees* for infotainment and mobile business. Specifically, the wireless technology needs to deal with the following characteristics of vehicular mobility:

1. high mobility: vehicles are moving at high speed
2. constantly changing network topology: relative positions to the base station and to peer vehicles are constantly changing
3. short duration within base station coverage area: due to high traveling speed, each vehicle only stays within the coverage area of one base station for a short period of time.

Such difficulties pose challenges to the design of protocols, from the physical layer up to the application layer.

1.3 Comparison of Different Technologies

A multiplicity of wireless technologies that are either being tested or already in service are available for use in Vehicular networks. Some of these could be viable candidates in vehicular applications, such as WiMAX (Worldwide Interoperability for Microwave Access, IEEE 802.16) [WiMAX01] and HSDPA (High Speed Downlink Packet Access for 3G) [3GPP02] ; a few technologies are still in the research stage, such as DSRC (Dedicated Short Range Communications, IEEE 802.11p) [DSRC02]. It is believed that none of the technologies will overtake the others. Instead each is expected to have its own specific area of application and will co-exist with others. The International Standards Organization (ISO) identifies all these technologies as ITS (Intelligent Transportation System) Wide Area Communications, and has set up a task group to combine all these related standards into one open architecture called Continuous Air interface for Long and Medium distance (CALM), as shown in Figure 1.1.

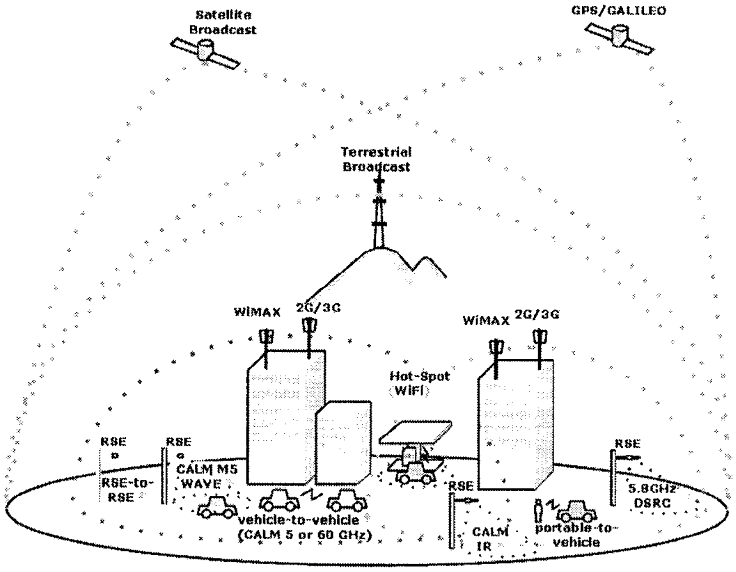


Figure 1.1: The CALM Model ([ISO93])

Of these technologies, HSDPA lacks the direct car-to-car communication capability, so we will focus our discussion on WiMAX (IEEE 802.16e) and, more importantly, DSRC (IEEE 802.11p). Hereinafter, we will use the term IEEE 802.11 and WiFi interchangeably.

WiMAX was firstly developed as a technology for fixed wireless access in Metropolitan Area Network (MAN). Following the approval of the IEEE 802.16e standard in December 2005, which is specifically designed for mobile access at vehicular speeds by adding a higher layer handoff mechanism between base stations and sectors, WiMAX has become a viable option for vehicular networks, both for vehicle-to-vehicle and vehicle-to-base station applications. Its advantage is that IEEE 802.16e inherits centralized control mechanisms from the IEEE 802.16 family, thus can offer a rich set of QoS controls and much better throughput than the distributed coordination Carrier Sensing Multiple Access (CSMA) scheme typically used in IEEE 802.11 networks. Moreover, WiMAX is allowed to use higher transmission power, thus, WiMAX has a much larger transmission range than WiFi. In practice (under non-ideal conditions), one WiMAX base station's transmission range can reach as far as 5-7 kilometers. Having a longer transmission range greatly offsets the network volatility caused by high mobility of the nodes.

The issues faced by WiMAX in vehicular applications are three fold. First, in many countries there is no licensed frequency band allocated for WiMAX in vehicular applications to date. If WiMAX has to work on the free-to-use frequency bands, WiMAX will have to reduce the transmission range due to interference of other transmission sources, and possibly can only operate within a range of few hundred meters (similar to WiFi networks). Second, WiMAX base stations typically have transmission power at the level of cell phone towers (10-20 watts), or even higher if further transmission range is needed. Public acceptance of these towers and the impact on human health could be an issue. Third, FCC regulations limit the transmission power on mobile terminals (i.e. less than 1 watt). Thus although base stations can reach mobile terminals as far as 50 kilometers away in ideal conditions, mobile terminals may not be able to reach the base station. Further, increased transmission range of mobile nodes means lower network capacity due to decreased special reuse of channels.

The other technology, IEEE 802.11p (DSRC) also has some advantages and disadvantages. First, to provide reasonable coverage and duration time, the new 802.11p standard has extended the base station transmission range from 100 meters in the traditional WiFi to 1 kilometer in DSRC. Second, less transmission power means it is easier for neighborhood residents to accept a base station tower. Third, the FCC has allocated licensed frequency bands in the 5.9 GHz band for use in DSRC. Figure 1.2 shows the schematic of DSRC protocol stack, and Figure 1.3 shows the FCC band plan for DSRC.

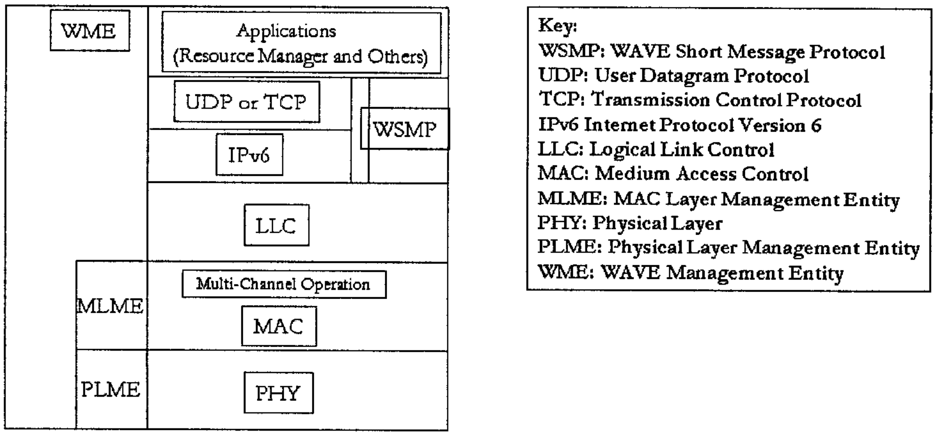


Figure 1.2: DSRC Protocol Stack ([DSRC02])

The FCC has allocated 7 channels for DSRC, including one control channel and six service channels. Safety related packets will normally be transmitted in the control channel, while other six service channels can be used for commercial purposes.

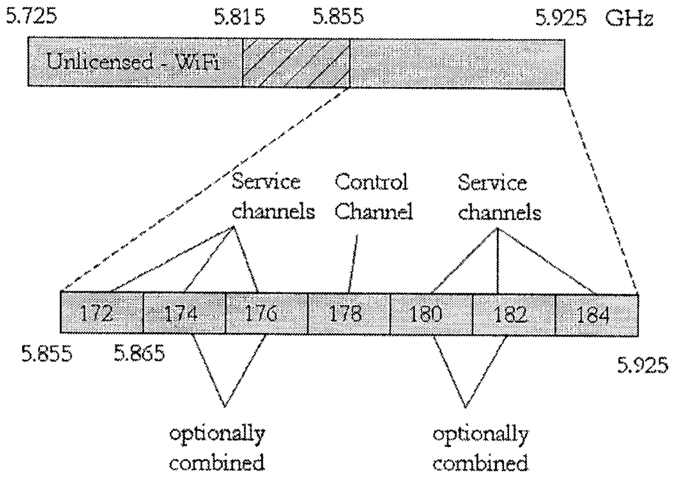


Figure 1.3 FCC Band Plan for DSRC ([FCC-DSRC03])

However, adapting the IEEE 802.11 protocol to a vehicular environment still faces some serious challenges. First, traditional IEEE 802.11 MAC protocols are designed to operate with the CSMA/CA mechanism in Distributed Coordination Function (DCF) mode, which assumes that the network is not heavily loaded and mobile nodes are within a small area space (<100 meters in radius). Therefore mobile nodes can use the DCF Inter Frame Space (DIFS) to test whether the channel is busy. However, vehicles can be very densely distributed (i.e. during a traffic jam or in slow moving traffic) and thus the network could be heavily loaded. Moreover, it is almost impossible to enforce end-to-end Quality of Service in multi-hop networks using the CSMA/CA mechanism, because no stable link is maintained and the routing decision for each packet is made on-the-fly.

Second, the IEEE 802.11 protocol was originally designed for use in isolated hotspots; it has no built-in handoff mechanism. It is obvious that without continuous coverage, WiFi is not a viable technology for fast moving vehicular networks. However, recently the applications for WiFi networks have shifted away from isolated hotspots to WiFi mesh networks, where WiFi base stations are densely placed in many cities to provide seamless coverage within certain districts. This recent trend provides the opportunity to provide "always-on" connection to vehicles on highways. We hence adopt the IEEE 802.11 technology as the basis for our vehicular network architecture.

In our architecture, we propose to place base stations along the highway to form "continuous hot spots", and extend the Point Coordination Function (PCF) to Time Division Multi Access (TDMA) as the MAC layer protocol. Vehicles within the range of one hotspot are included in one cluster, and the base stations naturally serve as cluster heads. The transmission and receiving time slot of each node are assigned by the cluster head. When a node needs to establish a connection with another, it sends its request to the cluster-head. Based on the wireless signal interference model, the cluster head assigns appropriate channels to intermediate nodes for the request.

The contributions of this thesis are as follows:

1. Proposing a generic TDMA scheme prototype at MAC layer for IEEE 802.11 to facilitate high-speed data connection in Vehicular Ad-hoc Networks (VANET) using car-to-car and car-to-base station multi-hop connections.
2. Devising and implementing a greedy algorithm for channel assignment based on the new protocol.
3. Identifying key parameters affecting network throughput.
4. Performance evaluation of the devised greedy algorithm for a variety of network and

traffic conditions.

This thesis is organized as follows. Chapter 2 introduces the related work on routing and packet dissemination algorithms for Vehicular Ad-hoc Networks (VANET) and Mobile Ad-hoc Networks (MANET). In Chapter 3, the greedy channel assignment algorithm is introduced. In Chapter 4, various simulation scenarios and results are discussed. Finally, Chapter 5 presents conclusions and future work.

CHAPTER 2

RELATED WORK

In Chapter 3, we are going to introduce our new system architecture; our focus is on its medium access control (MAC) mechanism, how connections are set up and data flows are established. Before we proceed to Chapter 3, it is beneficial to survey the proposals on VANET based on traditional system architecture, especially those proposals on similar functionalities. In this Chapter, we use the term *traditional system architecture* to refer to the network with no infrastructure support (i.e. no base stations or access points) available, or only when isolated hotspots are available. In this kind of system architecture, routing is performed using a distributed algorithm; IEEE 802.11 protocol's CSMA/CD mechanism is used for medium access control.

We surveyed the proposals in the following three areas: data exchange, routing, and coordination mechanism at the MAC layer. These areas are where traditional system architecture differs from our new system architecture. Most of the proposals are on Vehicular Ad-hoc Networks (VANET), some of the proposals are on the more generic Mobile Ad-hoc Networks (MANET)

This chapter is structured as follows: Section 2.1 discusses proposals on data exchange in VANET; Section 2.2 discusses proposals on routing and clustering algorithms in Mobile Ad-hoc Networks (MANET); Section 2.3 discusses MAC protocol proposals in VANET.

We then give a summary in Section 2.4 and point out limitations of the traditional system architecture.

2.1 Data Exchange Algorithms in VANET

2.1.1 Overview

In recent years quite a few data exchange models have been proposed for VANET ([LA05], [CS02], [FCC05], [WF04], [NTK06], [ZC05]), most of them describe a pure vehicle-to-vehicle ad hoc network with no infrastructure support, i.e. no base stations or internet gateways placed along the road. Some of them assume there are base stations and Internet gateways in the system architecture, but they are distributed sparsely along the highway, so the vehicle-to-vehicle ad hoc wireless connection is used as an extension to the wired infrastructure.

One important characteristic of these schemes is that flooding is used as the means of message dissemination. Flooding the network means upon receiving a packet, each node re-transmits the packet to all its neighboring nodes. This is due to either the assumption that the accurate location of the destination node is not known so that no route can be established from sender to receiver as in [WF04]; or to the design goals of the system, which are to disseminate the packet to as many nodes as possible as in [WXY05]. Since flooding introduces redundant packets in the network, the key element of this kind of approach is to suppress the re-transmission of redundant packets.

2.1.2 Model 1 MDDV: A Mobility-Centric Data Dissemination Algorithm for Vehicular Networks ([WF04])

This model is a typical data exchange model that could be classified as "Restricted flooding" or "Smart flooding". Vehicles traveling along the road form an ad hoc wireless network and exchange information with each other. The authors of this paper assume that, due to some security concerns, each vehicle's exact location is not made public. Therefore, information is passed from source node to destination node by flooding the packet throughout the network. The road network topology is non-trivial (i.e. not simply a straight line), and is represented as a graph, as shown in Figure 2.1.

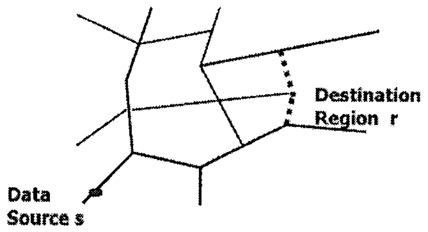


Figure 2.1 Geographical-Temporal Multicast ([WF04])

However, flooding the networks without any control may degrade system performance. To deal with this problem, the authors proposed a mechanism to suppress redundant message transmission during flooding. The mechanism divides nodes (vehicles traveling on the road) into two categories:

a. Non message holder

b. Message holder, which is further divided into two categories:

 (1) message head candidate

 (2) non-message head candidate

Each message holder keeps a Message Head pair (*t*, *l*) for each message stored in its buffer.

Variable t is the time when the message is received by this node and l is the location where the message is received. For simplicity, it is assumed that the message holder will move towards the destination.

Upon receiving the message, each node records a Message Head pair (t_r, l_r) for this message. Then each message holder keeps comparing current time t_c with the message receiving time t_r: if $(t_r - t_c) < T_1$ (here T_1 is a system wide parameter), this implies that the message was just propagated to it a short while ago, thus the node considers itself still in the "wave front" of the message, and it sets itself as *message head candidate*. In this case, if $(t_r - t_c) < T_2$ and $(l_c - l_r) < L_2$ (here T_2, L_2 are system wide parameters), the message head candidate is in *active mode*, and propagates messages actively. On the other hand, if $T_2 < (t_r - t_c) < T_3$ and $L_2 < (l_c - l_r) < L_3$ (here T_3, L_3 are system wide parameters), the *message head candidate* is in passive mode. In this mode, the node will not transmit messages, unless it receives an "older" message broadcast, i.e. the value l of a message pair overheard points to a node that is further than the one corresponding to the message stored in its buffer, or t is later than the stored message head.

The node considers itself as *non-message head candidate* in the following 3 cases:

a. the node moves away from the destination along its current trajectory

b. the node receives a "newer" version of the message, where the new message contains $<t_n, \quad l_n>$, t_n is closer to the destination than t_r in the recorded message head:

c. $(t_r - t_c) > T_1$

Dropping the stored message is by discretion, when the node believes that the message is out of date and will no longer assist in message passing, i.e. when the node receives a "newer" version of the message, or the current time is much greater than the received time.

2.1.3 Model 2 PPB-IGS: Peer-to-Peer Broadcasting Information Guided Search For Resource Discovery ([WXY05])

One interesting problem in vehicular ad-hoc networks is about resource discovery in urban roads. A typical scenario consists of vehicles moving along the streets in the city looking for scattered resources (i.e. parking lots or gas stations). To retrieve the resource information, the ideal scenario is that a vehicle contacts a resource server through the cellular network and receives the information almost instantly. The authors propose another way of retrieving this information by vehicles exchanging the information with each other in a vehicular ad-hoc network.

First, information relevancy is determined when a vehicle receives the message from peer vehicles. Assume vehicles arrive at a resource (thus may consume the resource) according to a Poisson process. Vehicle V moves at a constant speed v and receives a report that is generated t time units earlier, which indicates a resource at distance d from the vehicle's current location. The resource relevancy to this vehicle is defined as

$$\mathrm{R} = e^{-(\lambda t + \lambda \cdot d / v)}$$

Here, λ is the average arrival rate of vehicles.

The algorithm is as follows:

Peer-to-Peer Broadcasting (PPB): each vehicle listens to the broadcasting of other vehicles. The resource reports from other vehicles are stored in a local buffer and sorted according to their relevancy. The vehicle broadcasts the top M files in a local buffer periodically.

Information Guided Search (IGS): at the beginning all the vehicles are moving around blindly, when a vehicle moves pass a resource, the vehicle discovers the resource and add the resource report to its local buffer. A vehicle that receives this report will head on to the resource following the shortest path. If the vehicle receives a resource report on the way that has higher relevance, the vehicle moves to the new resource. If the vehicle arrives at the resource site but the resource is already taken, the vehicle resumes blind search mode. A similar model using a swarm algorithm is proposed in [DNP04].

2.2 Clustering and Routing Algorithms in Mobile Ad hoc Networks (MANET)

2.2.1 Overview and Comparison with VANET

In traditional system architecture, there is no infrastructure support. Therefore, routing and clustering requires special effort. Typically, routing strategies in MANET can be classified into three categories: reactive, proactive and position based. In reactive routing, routing decisions for each packet are made at each node based on current connectivity, i.e. no end-to-end connectivity is assumed. An example of reactive routing is the Dynamic Source Routing (DSR) ([JM96]) algorithm.

Proactive routing requires each node to maintain the link state of the whole network. An example is Optimized Link State Routing (OLSR) [TP03]. The source node usually keeps the path (or a next hop lookup table) to every destination node. The advantage for this approach is that routing decisions can be made quickly; the disadvantage is that maintaining link state information consumes some bandwidth in mobile networks. The third approach is the position based routing, e.g., Greedy Perimeter Stateless Routing [KK00]. The routing decision is based on the exact location of the destination node.

Managing mobile nodes by clustering is not a new technique in mobile ad hoc networks. Clustering is performed by partitioning the network into overlapping or non-overlapping parts to facilitate routing and QoS management. There are many algorithms proposed for clustering in MANETs. A survey on clustering in MANETs is presented in [YC01]. The general idea of cluster formation can be abstracted to finding the minimum dominating set (MDS) or minimum connected dominating set (MCDS) in a graph, as described in [YFM02].

Clustering algorithms for MANET must take node mobility into account for the creation and maintenance of clusters. It would help greatly if algorithms can incorporate node mobility prediction to increase the temporal stability of clusters. However, there are quite a few different mobility models used in MANET, and an experiment described in [VS05] concludes that the effectiveness of a predictive clustering algorithm depends heavily on the underlining mobility model. In the random-way-point model, which is widely used in

MANET algorithm analysis, the predictive algorithm behaves poorly.

Under traditional system architecture, routing and clustering in VANET can be considered as a special case in MANET. In VANET, clustering is enhanced by the presence of on-board GPS units or by the use of localizing techniques such as the one described in [BEN05]. Further, the distribution and movement of the mobile nodes are highly constrained by the layout of the road networks. The challenge here is how to deal with high node mobility, and the rapid network change incurred by node mobility poses special challenge to algorithm design.

Holger Fubler et al ([FM02]) conducted a comparison of routing strategies for vehicular ad-hoc networks. In their work they concluded that position based routing is more suitable than routing without position information in VANET.

This section does not intend to serve as an extensive survey on MANET clustering and routing algorithms. Instead, the algorithms shown are examples demonstrating how the clustering algorithm works in MANET and VANET in the traditional architecture. In section 2.2.2 and section 2.2.3, two clustering algorithms in MANET are introduced. One algorithm groups only one-hop neighbors into clusters [KVCP97], the other form clusters that have multi-hop neighbors. Then an algorithm to enhance clustering stability in MANET is introduced in section 2.2.4. We then introduce DSR and AODV routing algorithms in section 2.2.5 and section 2.2.6, respectively.

2.2.2 Model 1: Cluster with One-hop Neighbors ([KVCP97])

The purpose of this algorithm is to divide a graph into overlapping clusters, where each cluster is a clique in the graph, i.e. each node in the cluster has connections with all the other nodes in the cluster. The border nodes are the nodes that have membership in two or more clusters. Node mobility is simplified into four cases: Node A switches on, Node A switches off, Node A connects with Node B, and Node A disconnects with Node B. In the following we only describe the case when Node A turns off, other scenarios can be handled similarly [KVCP97].

When Node A switches on, A notifies all the neighbors of its arrival, and receives the cluster name and the neighbor list of all its neighbors. Node A initiates *Create Cluster* function, which creates new clusters in the neighborhood of A. Node A then initiates *Find Essential* function to identify non-overlapping clusters in the graph after the new clusters are generated. After *Find Essential* function is done, Node A initiates *Find Redundant* function to remove the redundant clusters from the graph. Finally, Node A broadcasts the new cluster list and boundary node list to the rest of the network.

The *Create Clusters* function is the core of the algorithm. The algorithm iterates through all the neighbors of Node A and identifies different cliques from these neighbors. Node A clique is a cluster. Redundant clusters, i.e. clusters totally contained in other cluster, or clusters that totally overlap with other clusters, can be formed from this process. These kinds of clusters will only be created in the neighborhood of Node A, since only those clusters are affected.

The *Find Essential* algorithm finds the largest non-overlapping clusters after all the new clusters are identified. This algorithm first sorts all the clusters in the graph by non-descending order in cluster size, and clusters are searched in this order. If a cluster contains a node which is also in another cluster, this cluster is marked as non-essential. All the essential clusters are then attached to the local-list, which contains the original neighboring clusters A received when it first turned on.

The *Find Redundant* algorithm goes through all the clusters in the local list to see if any cluster in the list is covered by other clusters. If so, this cluster is removed. The algorithm for Node A switches off, Node A connects B, and Node A disconnects B are similar.

After the whole algorithm is run, the graph is divided into overlapping clusters. Each node in the same cluster proactively maintains the routing table for the cluster, inter clustering routing is performed by boundary nodes that connect two or more clusters, thus greatly improving path finding efficiency.

2.2.3 Model 2: Clustering by Preferred Neighbor Election ([NB04])

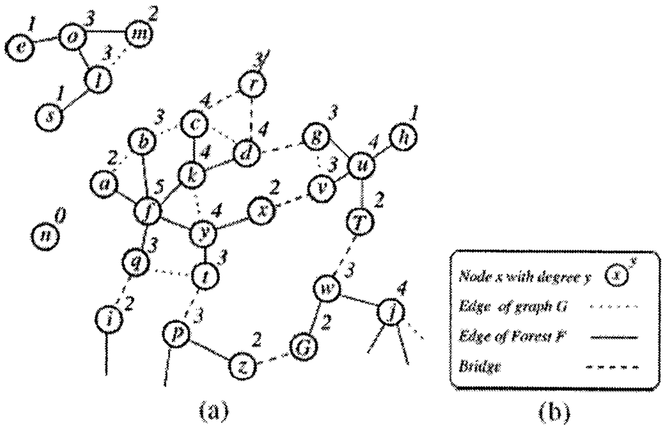
In this algorithm, *Preferred Neighbor* is defined as the neighboring node that has the largest degree. Depending on how many Preferred Neighbors (PN) a node has, nodes in the graph are divided into 3 categories:

No PN – nodes has no neighbor

Single PN – if the node has only one PN, then the PN will become the elected PN

Multiple PN – if the node has more than one PN, then any tie-breaking rule can be used to determine the elected PN, e.g. the PN with the highest id.

Each node determines its degree and broadcasts the degree information using normal beaconing messages to neighboring nodes. Once the node determines its elected PN, it notifies its elected PN and establishes connection with it, as shown in Figure 2.2:



(a) (b)

Figure 2.2 Preferred Neighbor Examples

(a) the constructed forest (b) legend ([NB04])

In Figure 2.6, Node k connects with Node f, and Node z connects with Node p. It can be shown that, given any network topology, this algorithm always yields a forest, i.e. acyclic graph..

After the nodes are connected to their elected PN, each node exchanges its neighbor information with its PN, thus the membership information of one cluster is propagated to each member. Inter-cluster communication is naturally established by neighboring nodes that are not elected PNs to one another.

Cluster maintenance in the case of moving nodes is easily achieved by periodically updating the network topology, by each node listening and broadcasting the neighboring/connection information.

2.2.4 Model 3 SERC: Smooth and Efficient Re-Clustering ([KM05])

This is a surprisingly simple but powerful algorithm. In a cluster with cluster head structure, two cluster heads are selected for each cluster, the Primary Cluster Head (PCH) and Secondary Cluster Head (SCH). SCH synchronizes with PCH by caching the packets, when PCH fails or leaves the cluster, the Secondary Cluster Head takes over, either by explicit signaling from the PCH, or by losing beacon signal from the PCH. In the proposed selection algorithm, PCH and SCH are selected by battery power level and relative proximity.

2.2.5 Dynamic Source Routing (DSR)

Dynamic Source Routing is a reactive routing protocol ([JM96]). It enables a source node to find a multi-hop source route to any destination in a mobile ad-hoc network. The protocol is divided into two parts: *Route Discovery* and *Route Maintenance*. Route discovery and route maintenance functions work on demand, thus keeping the overhead for routing table updates at minimum. The protocol works as follows.

Route Discovery: When a source node, denoted S, wants to send a data packet to a destination node, denoted T, Node S first searches its local cache for existing *source route* leading to Node T, which is basically a sequence of intermediate nodes that the packet should be relayed to Node T. If such a route exists, Node S attaches the source route to the header of the data packet, and the packet is transmitted to the next hop. If no such route exists, then the source node initiates a *Route Request* message and broadcasts the messages to its neighbours. The route request message contains a *route record list*, which is initialized to an empty list by the source node. Each node other than destination Node T will append its node id to the route record list, and re-broadcast the packet. If the destination node T receives the packet, it returns a *Route Reply* packet and attaches the route record list. The destination node sets the path for the route reply packet by reversing the route record list.

To suppress unnecessary route request packet transmission in the network, each route request packet carries a request ID. Request packets with the same request ID will not be processed by receiving nodes. Each node can update its routing table by overhearing the transmission of other nodes. Thus the overhead of routing table update is kept low.

Route Maintenance: each intermediate node in the path of a packet is responsible for confirming the transmission to the next hop. This can be done in various ways, for example, the previous hop can overhear the transmission of the next hop, or the confirmation is achieved by link-layer acknowledgement. If a broken link is detected (i.e. a packet is re-transmitted for maximum times), a *Route Error* packet is generated and sent back to source node S. If source Node S has other routes to destination T (for example, by overhearing another node's transmission), Node S will re-transmit the packet following the new route. Otherwise, Node S will need to initiate a new Route Request packet.

2.2.6 Ad-hoc On Demand Distance Vector Routing (AODV)

AODV ([PR99]) is another reactive routing algorithm for MANETs. The path finding algorithm in this protocol can be divided into two parts: Reverse Path Setup and Forward Path Setup. When a source node S wants to sent a packet to destination node T, Node S first broadcasts a *RREQ* packet. This packet contains the following information: <source_addr, dest_addr, broadcast_id, source_sequence_number, destination_sequence_number, hop_count>. If the intermediate nodes receive the RREQ packet with the same source_addr, destination_addr and broadcast_id, it will discard the repeated packets.

If an intermediate node does not have a route in its local cache that leads to the destination node, or if the route in the local cache has lower destination_sequence_number than in the *RREQ* packet, this node cannot reply to the *RREQ* packet. It records the first node that it receives this packet from, and then re-broadcasts the *RREQ* packet. Therefore, when the packet arrives at the destination node, it leaves behind a trail of intermediate hops. A reverse path is thus set up automatically.

If an intermediate node (or the destination node itself) can reply to the *RREQ* packet, it sends a *RREP* packet to the source node containing the following information: < source_addr, dest_addr, dest_sequence_number, hop_count, life_time>. When the *RREP* packet is relayed to the source node, each intermediate node sets up a forward link, just like the reverse path setup during *RREQ* packet relay. When the source node receives the *RREP* packet, it updates its destination_sequence_number and begins transmitting packets. A forward path is thus setup. Later, if other *RREP* packets come back with a better route (i.e. a path with a smaller hop count), the source node can switch to the new route.

Since reverse path is marked at every node receiving broadcast *RREQ* packets, if the reverse path is not used, it should be removed from the routing table. This is done through a *route_request_expiration_timer*. Another timer, *active_timeout* is used to determine whether an intermediate node on the path is active. If it originates or relays at least one packet during the active_timeout, then this node is active. Otherwise, the node is not active and the link is broken. In that case, the node upstream in the path generates a *RREP* packet to the source node informing the broken link. Upon receiving this unsolicited *RREP* packet, the source node initiates a new path finding process as described above.

In conclusion, clustering and routing in traditional architecture requires extra processing at each mobile node. Due to lack of infrastructure support, mobile nodes need to constantly exchange neighbourhood information, and keep a routing table for packet relaying. Cluster maintenance sometimes requires complicated computation to be performed on mobile nodes, such as Model 1 introduced in [KVC97]. These tasks impose burden on the mobile nodes, and occupy certain bandwidth in the network. In Chapter 3, we introduce a new architecture that, with infrastructure support, relieves mobile nodes from these resource consuming tasks.

2.3 MAC Layer Protocol Proposals in VANET

2.3.1 Overview

The design of a MAC layer protocol is a heated topic in the VANET literature. The MAC protocol in DSRC is based on the IEEE 802.11 standard. In most cases, medium access control in 802.11 protocol is based on the Distributed Coordination Function (DCF) mechanism, which is a random access scheme using Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). To solve the hidden node problem, request-to-send (RTS) and clear-to-send (CTS) packets are exchanged before data packet transmission. Another medium access control mechanism in 802.11 is called Point Coordination Function (PCF) which uses infrastructure support. DCF is a distributed control mechanism using exponential back off to avoid medium access collision. PCF, on the other hand, is centralized scheme and can achieve collision free time-bounded medium access.

MAC layer design needs to address the following challenges in VANET:

(1) Safety applications demand collision free MAC protocol to send out traffic warning packets. Since it is assumed that, in traditional system architecture, no infrastructure

support is available most of the time, therefore safety warning packet transmission should be provided when, i.e. using the DCF mechanism

(2) In a highly mobile environment such as Vehicle-to-Roadside communication (V2R), a MAC protocol should be able to ensure high data throughput for short connection periods. An example is when a vehicle passes by a base station to download from the Internet. If the vehicle moves at 100km/h (27m/s), and if the signal coverage of the base station is 800 m, the connection time is less than 30 seconds. This requires highly efficient medium access mechanism.

(3) Also, multi-channel operation in DSRC is challenging, because radios demodulate one channel at a time. If a vehicle transmits a safety message through one channel, and the nearby vehicle is downloading movies using another channel, the message is not received.

In [ZR03], MAC protocols in VANET are classified into two categories, as shown in Figure 2.3:

(1) Vehicle-to-Vehicle (V2V): DCF

(2) Vehicle-to-Roadside Unit (V2R): DCF and PCF (using base station as coordinator)

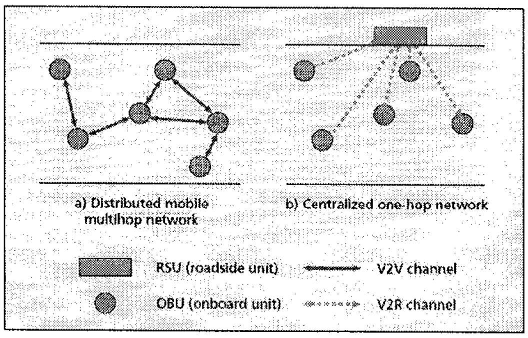


Figure 2.3 Two Basic Scenarios of a DSRC system ([ZR03])

In this section, we show various proposals for MAC protocol in VANETs. Some of the proposals assume there is an isolated base station that can assist on medium access (i.e. [ML05]), some of the proposals assume no infrastructure support (i.e. [KE05], [YLZ04]). Before we proceed to Chapter 3 and introduce our system architecture and MAC layer protocol, to see how the problems are addressed under traditional system architecture, it is beneficial to review these proposals.

2.3.2 MAC in the Presence of Roadside Units ([ML05])

[ML05] proposed a MAC protocol for multi-channel operation in the presence of roadside units. The purpose is to ensure that safety messages have an opportunity to transmit every 100 ms near roadside units, and also maximize the bandwidth for non-safety connections. To do that, a roadside unit is used to provide synchronization and channel coordination to the nearby vehicles. In the control channel, time is partitioned into periodic, regulated intervals, called the repetition interval, as shown in Figure 2.4:

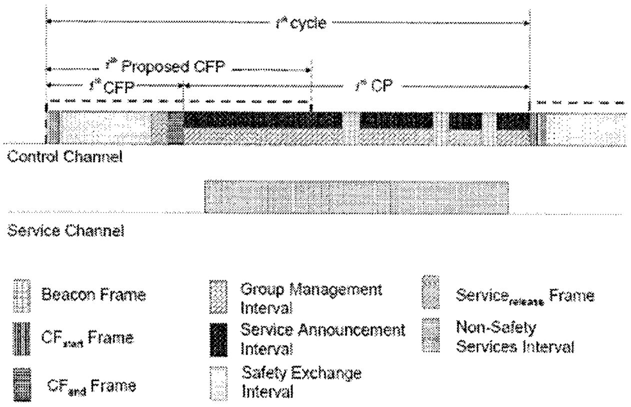


Figure 2.4 Frame Structure ([ML05])

CFP is the contention free period. During this time period all the vehicles within a certain range are polled and allowed to transmit safety messages. If the vehicle polled does not have any safety message to send, it transmits a short null frame. During the contention period (CP), the following actions can be taken.

(1) Vehicles located in the service region can switch to service channels, after listening to the service announcements by the roadside unit.

(2) Vehicles can send safety messages using the distributed DCF protocol

(3) Roadside units perform group management to update the polling list, i.e. to include the new nodes and remove vehicles moving out of range from the polling list.

(4) The roadside unit transmits beacons to indicate the range of the next CFP. Vehicles receiving this beacon should remain silent until polled at the next CFP.

(5) The schedule for the next CFP is indicated in the $\text{service}_{release}$ frame, as shown in Figure 2.4.

By separating the period for safety message exchange from the period allocated for service (non-safety related messsages), this protocol ensures that the vehicles within the polling range have sufficient time to exchange safety messages with each other, and also it maximizes the time span for service channels (note that if a vehicle does not have a safety message to send out, it only transmits a short null message).

2.3.3 A Single-Hop Service to Broadcast Safety Warning Messages ([XM04])

[XM04] proposed a single-hop service to broadcast safety warning messages. This protocol is designed to deliver these messages with high probability within the message life time (since DSRC standard mandates that the control channel be polled every 100 ms, the life time is 100ms). The design goal is achieved by packet repetition during a packet's life time. The basic scheme of the protocol is as follows: a MAC extension layer is added between the MAC and LLC layers. When a message is passed down from LLC, the MAC extension transits from IDLE to REPETITION GENERATION state. In this state the system schedules multiple repetitions of the message in the selected time slots within the life time. Each repetition is an event with a slot number. All these events ordered by slot numbers form a queue called the Packet Event Queue. Once the queue is formed, the system returns to IDLE. When a packet event arrives, the MAC extension transits from IDLE to DISPATCH, passing the packet down to MAC. When a packet is passed up by MAC, the layer checks if the packet is new or not. If the packet is new, the packet is passed up to LLC. Otherwise the packet is eliminated.

The authors tested this scheme with the following variances: asynchronized repetition vs. globally synchronized repetition at fixed time slots, repetition using k slots vs. each slot for $\frac{k}{n}$ probability, and adding modified MAC using carrier sensing (drop packet without back-off). The authors reported that the best protocols are synchronous fixed repetition, and asynchronous fixed repetition with carrier sensing. Considering that synchronous fixed repetition requires synchronizing to a global clock, the asynchronous fixed repetition with carrier sensing is thus the best choice. This result can be explained by noting that repetition gives a node more chance to send, and carrier sensing causes interfering nodes to stop transmitting.

2.3.4 DRVC (Direct and Relay Protocol for Vehicle Communications ([DI04])

Reference [DI04] sketched the design of MAC protocol in the presence of roadside units called DRVC (Direct and Relay protocol for Vehicle Communications). In DRVC, roadside units listen to the inter-vehicle communications, once the roadside unit detects a failed link between the vehicles, the roadside unit relays the packet. The intention is to achieve low delay and high throughput.

The frame structure of DRVC is shown in Figure 2.5:

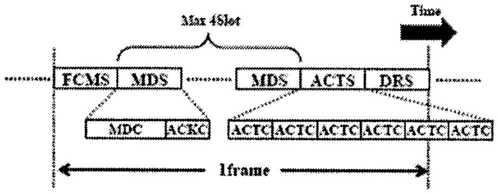


Figure 2.5 DRVC Frame ([DI04])

The frame is of variable length. Each frame consists of a frame control message slot (FCMS), a message data slot (MDS), an activation slot (ACTS), and a data relay slot (DRS).

-FCMS is used by the roadside unit to declare frame information and synchronize all the vehicles in the cell;

-MDS is used to transmit data, it is further broken down into two mini slot channels, several message data channels (MDC), and an ACK channel (ACKC).

-ACTS is used for the vehicles to reserve MDS slot, it contains six data activation channels, as in DSRC specifications.

-DRS is used for the roadside unit to relay data when the communication link between two vehicles fails, i.e. the roadside unit does not hear the reply for one packet.

The roadside unit first transmits FCMS to declare the allocation of MDS. Each vehicle then begins to transmit data in the MDS, and acknowledges data using ACKC in the MDS. The roadside unit listens to all the data traffic. Once the roadside unit detects one ACKC is missing, it assumes that the transmission is not successful and transmits the packet to the destination vehicle. Possible extensions could be that the roadside unit assigns a master vehicle in a group of vehicles, and that the master vehicle assumes the function as described above.

There are a lot of details not mentioned in the above description, such as the data traffic volume between the vehicle since the roadside unit obviously needs to cache a lot of packets, and how this protocol works on multi-channel operations. The authors intend to work out more details in future research.

2.3.5 Distributed Algorithm for Warning Message Sending Rate ([YLZ04])

[YLZ04] investigates the design of a MAC layer protocol from another angle. Normally, if a vehicle encounters an accident on the highway due to weather conditions, it is very likely that other vehicles may encounter similar conditions in the same section of the highway. If all these vehicles, located in close proximity, start transmitting warning messages in the control channel, chances are the channel may be jammed by all these messages. Therefore it is necessary to reduce the warning message transmission rate after some time, to make room for other nodes to broadcast.

Three challenges are identified in designing this protocol. The first challenge is that the emergency warning message has very stringent delay constraint, while the link quality in V2V communications can be very bad due to multipath fading, shadowing and Doppler shifts caused by vehicle mobility.

The second challenge is the need to support multiple co-existing abnormal vehicles (vehicles that enter into abnormal condition either by having an accident, or by emergency braking/steering). Some vehicles will move away from the scene, but the vehicles that had an accident will stay for some time, remaining as a threat for the incoming traffic. How to prevent these vehicles from jamming the control channel is a problem.

The third challenge is the differentiation of emergency events and elimination of redundant warning messages. If a car suddenly brakes in the highway, causing following cars to brake, all these cars will start sending out emergency messages. Obviously, the foremost car shouldn't send out the warning message occupying the control channel, if the car behind it is sending out warning messages.

The authors tried to solve this problem by setting a decreasing message sending rate for each vehicle that enters abnormal mode. When a vehicle enters the abnormal mode for the first time, it enters *initial AV state*. In this state the vehicle transmits packets with an initial rate λ_o. As time passes, the warning message transmission rate is decreased by a factor of α after L transmitted warning messages, until the minimum rate $\lambda_{\min}$ is reached.

The vehicle can further decrease its message sending rate to zero by entering into *non-flagger state*, when it receives warning messages from the car behind it. At this time there is no need for the vehicle to warn the incoming traffic, because the vehicle behind it is sending the warning message.

The vehicle behind the first abnormal vehicle may move on, i.e. after avoiding the collision with the first car, the cars behind will keep going ahead. If for some time T the initial vehicle does not hear any warning messages from behind, it starts transmitting warning messages at $\lambda_{\min}$ again.

2.3.6 Enhanced DCF for VANET ([XN04])

[XN04] proposed to use enhanced DCF in place of DCF for 802.11 MAC in VANET. The problem with legacy 802.11 MAC DCF is that all terminals compete for medium using CSMA/CA with equal priority. Quality of Service requirements for different applications are not recognized and hard to implement. To satisfy the stringent real time requirement for VANET safety warning messages, Enhanced DCF seems to be a viable choice. In EDCF, different QoS requirements are differentiated by setting different lengths for the back off window in the carrier sensing stage. High priority application packets can be assigned smaller control window size ($CW_{\max}$ -$CW_{\min}$), and smaller minimum back off time $CW_{\min}$ (which, combined with smaller window size, also implies smaller $CW_{\max}$)

Each application can be further differentiated by a different Arbitration Inter-frame Space(AIFS), as shown in Figure 2.6:

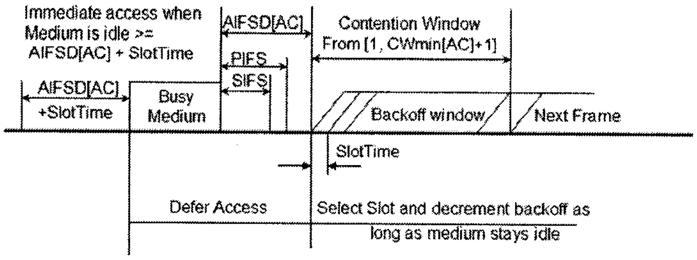


Figure 2.6 Time Sequence of EDCF ([XN04])

Simulation results show that EDCF satisfies the QoS requirements for delay sensitive traffic. However, under heavy system load, throughput of the system is sensitive to the contention parameters; moreover, in this case low priority traffic tend to have poor throughput.

2.3.7 Controlled Vehicular Internet Access Protocol (CVIA)

[KE05] proposed a novel MAC protocol that provides high throughput for internet access, called Controlled Vehicular Internet Access Protocol (CVIA). The basic idea for this protocol is to divide the road into segments, and control the active time of each segment.

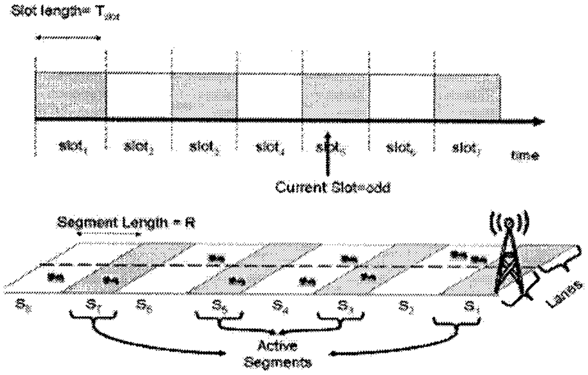


Figure 2.7 Controlled Vehicular Internet Access Protocol ([KE05])

As shown in Figure 2.7, at each time slot TS_j, only the vehicles in the active road segments are allowed to transmit. An active segment S_i is the road segment in which the time slot number j and segment number i are both odd or both even. Packet movement is as follows:

Packets are delivered in a packet train, i.e. multiple packets with only one RTS/CTS handshake. At each active segment, first each vehicle broadcasts its location to their neighbors in time $T_{\max,update}$. Immediately after $T_{\max,update}$, the vehicle that will carry all the packets to the next station as a temporary router, TR_i^{out} , is announced by the vehicle that carries all the packet into this segment, TR_i^{in}. Then the TR_i^{in} sends all the packets it carries to TR_i^{out} using packet train. Note that the packet train will not be interrupted here because all the local nodes remain silent. After the packet train is delivered, local nodes begin to send their packets to TR_i^{out}. Two exceptional cases need to be considered. First, if the packet train from TR_i^{in} takes time $>t_{\max,delivery}$ to deliver, after $t_{\max,delivery}$ the local nodes can interrupt and compete with the packet train delivery. Also, the "local gathering" phase will be cut off by the arrival of the next time slot, and the vehicle that carries all the data, TR_i^{out}, enters the next segment, becoming TR_{i+}^{in}.

To achieve fairness, each segment has a queue in the temporary routers. When forming the packet train, the packets from each segment are removed in round robin method.

2.4 Summary

In this chapter, we discussed proposals on data exchange, routing and clustering, and MAC level protocol for VANET and MANET. These proposals are all based on traditional system architecture. In traditional network architecture, there is no infrastructure support (i.e. no base stations or access points) available, or only isolated hotspots are available. Routing is performed using distributed algorithm; IEEE 802.11 protocol's CSMA/CD mechanism is used for medium access control.

We first discussed proposals on data exchange in VANET. Most of the approaches for VANET data exchange assume no end-to-end connectivity, and use network flooding to disseminate information. The drawback of this approach is that it can not support high speed connections, because the extra copies of packets will soon exhaust the network resources such as bandwidth and buffer.

We also discussed clustering and routing algorithms in mobile ad hoc networks (MANET). Clustering in VANET is a special case of MANET clustering. In VANET, it is typically assumed that vehicles are equipped with GPS, therefore node position information can be easily obtained. Further, node movement in VANET is constrained by the highway layout. These characteristics make clustering in VANET a little easier than in MANET. As to routing protocol, many routing protocols in MANET can be applied to VANET with minor modifications.

The limitations of all these clustering and routing protocols are that maintaining a cluster incurs significant computation overhead and/or communication overhead, due to the assumption that no infrastructure support is available. Also, it is difficult to maintain end-to-end connectivity due to high node mobility.

Finally, we introduced several proposals on MAC layer protocol for VANET applications. Many proposals use CSMA/CD as the medium access method, and try to adapt this mechanism to the fast moving, highly mobile environment in VANET. Some proposals, such as Controlled Vehicular Internet Access Protocol ([KE05]), address the limitations of the CSMA/CD protocol by designing a new spatial division medium access mechanism based on position of vehicles.

In this thesis, we take a different approach in addressing the issues. We believe that the PCF function in IEEE 802.11 protocol is a good candidate for the following reasons. First, distributed coordination function is not able to maintain end-to-end connection in highly mobile environment, thus it can not support high speed data connection; second, in high end applications such as VANET, base stations could be sophisticated enough to support this function. In fact, we take one step further and propose a centralized generic TDMA scheme in next chapter. Our system architecture supports high speed connection, end-to-end connectivity and clustering in VANET. One of the most important parameters for a new system architecture is the network throughput. After proposing the network architecture, we continue to study the problem of network throughput in Chapter 3.

CHAPTER 3

PROPOSED SYSTEM ARCHITECTURE PROTOTYPE AND ALGORITHMS

Chapter 2 introduces some proposed solutions for message propagation in the VANET literature. These proposed solutions are all based on CSMA/CD as MAC level protocol, assuming no centralized control. One inherent drawback in the pure distributed control mechanism at MAC level is the incapability to maintain end-to-end connectivity in mobile ad-hoc networks, let alone providing Quality of Service guarantees. Thus, existing proposals reviewed in Chapter 2 have limitations on supporting high speed connections in VANET.

In this chapter, we propose a new network architecture and MAC protocol based on a centralized control mechanism. This new network architecture supports high speed data connection using vehicle-to-vehicle wireless connections. Our focus is to study the network throughput under this network architecture. We formally define the network capacity problem and the greedy algorithm for channel assignments. Finally, we provide theoretical estimation for average network throughput.

3.1 Proposed System Architecture

In this section, we first introduce the infrastructure requirements in our system architecture. We then provide a brief description of the MAC layer protocol. After the introduction of infrastructure and MAC layer protocol, we describe the problem we want to address and simplifications of the problem.

In our system architecture, base stations are installed along the highway at fixed distance. According to the IEEE802.11p draft standard, each base station has a transmission range of 1000 meters. We place base stations 2 kilometers apart from each other. Each base station has 7 antennas, each dedicated to one of the DSRC channels allocated by FCC. Base stations act as network controllers; they can also act as Internet gateway if they are connected to backbone network. In the latter case, the base station can choose a nearby car to relay the data packet to the destination car, using vehicle-to-vehicle network. In this thesis, we focus on vehicle-to-vehicle connections and assume that all base stations work solely as controllers.

Each car has a GPS receiver, so that each car is aware of its position at any time. Further, the transceiver of each car has 3 antennas, one dedicated to the control channel, one dedicated to the sending channel and one dedicated to the receiving channel.

The placement of base stations divides the highway into clusters. Each cluster is a highway section of 2000 meters, with a base station placed at the center. Each base station is the head of the cluster. Cluster membership is controlled by the base station.

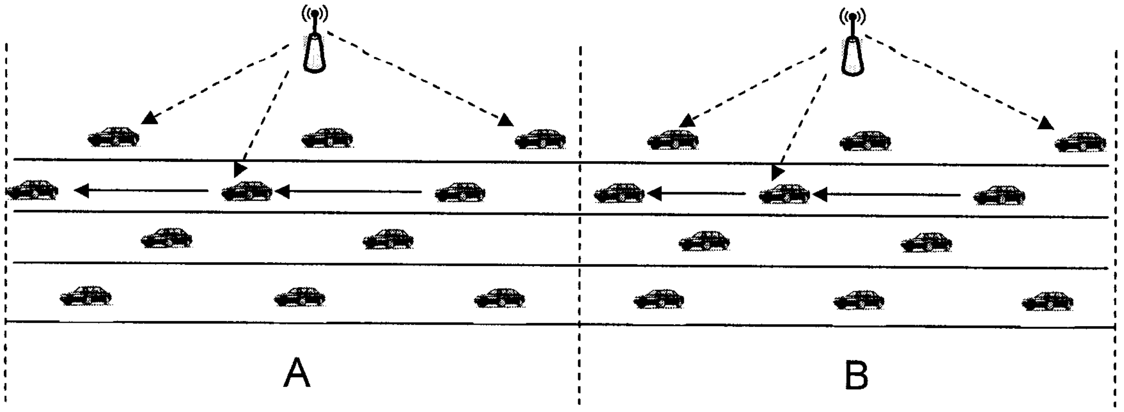


Figure 3.1 Proposed System Architecture (Two clusters A and B)

Figure 3.1 shows two clusters. Each cluster is 2000 meters in span. Base stations for cluster A and cluster B are located in the middle of each cluster, serving as cluster heads. Vehicles in each cluster are controlled by the cluster head (the base station).

The MAC protocol running on the infrastructure is a generic TDMA scheme. In this scheme, the base station chooses a set of relay nodes for each connection from source node to destination node based on the transmission range, and then assigns channels to each node for sending and receiving. Packet for the connection is then relayed in a multi-hop fashion.

This scheme assumes that nodes do not have significant relative movements. To counter the effect of node mobility in VANET, relay node selection and channel assignment are computed periodically. The frequency for this computation does not need to be very high. For example, if the speed difference between the fastest land and the slowest lane is 5 meters/second, it is often good enough for the computation to repeat every 1 second. This is because the relative disposition during 1 second, in the worst case, is only about 5 meters, which is negligible if the radio signal transmission range is 100 meters or more. For highway speed settings in our experiment, please refer to section 4.2.2 Experiment Settings. In our thesis, we assume that this interval for the above computations is given such that relative disposition of the nodes are negligible during the interval.

We give a general description of how the MAC protocol operates in the following paragraphs. We use the word "connection" to refer to a path from source node to destination node. The enumeration denotes the sequence in which different events happen.

1. If a vehicle wants to establish a connection with another vehicle, it submits its request to the base station through a request packet Connection-REQ containing the following information:

   < source_node_id, dest_node_id, TCP_port, connection_duration>

   A unique connection id can be obtained by concatenating source_node_id, dest_node_id, and TCP port.
2. Neighboring base stations exchange connection request information within each other's cluster. This information will be used for inter-cluster channel assignment.
3. Based on the location information of each vehicle in the cluster, and the connection request information in neighboring clusters, base station computes the channel assignment for each intermediate hops based on interference model (as defined in section 3.2).
4. At the beginning of the next scheduling interval, the base station broadcasts the channel assignment for each node in the cluster in the Channel-ASSN packet <node_number, receiving_channel, transmitting_channel, conn_id_to_send, conn_id_to_receive>. Here

the channel assignment scheme takes advantage of the fact that each node can both send and receive on different channels at the same time.

5. During the next scheduling interval, each node tunes its receiving antenna and transmission antenna according to the channel assignment;

Our focus in this thesis is not to provide a formal, detailed proposal of the protocol that utilizes the proposed architecture. Instead, our interest is in the problem of determining the network throughput, given the above prototype network architecture and protocol. In other words, how many connections can this network accommodate, and what are the parameters that affect network throughput. Specifically, we focus on the study of the network throughput within a single cluster, without the complications of inter-cluster interferences. We believe that solving this problem is important and fundamental to the understanding of the impact of a centralized control MAC scheme on network throughput, and provides a good bench mark for evaluating the effectiveness of inter-cluster scheduling algorithms.

To further simplify the problem, we observe that, in a typical 3-lane or 4-lane highway section, the width of each lane is much less than the transmission range. Each lane is around 5 meters wide, while transmission range can be as long as 100 meters. Taking this note, we can safely simplify the highway as a straight line, while vehicles are nodes placed on the straight line according to their location along the highway's stretch, ignoring the difference of lanes. This is shown in Figure 3.2.

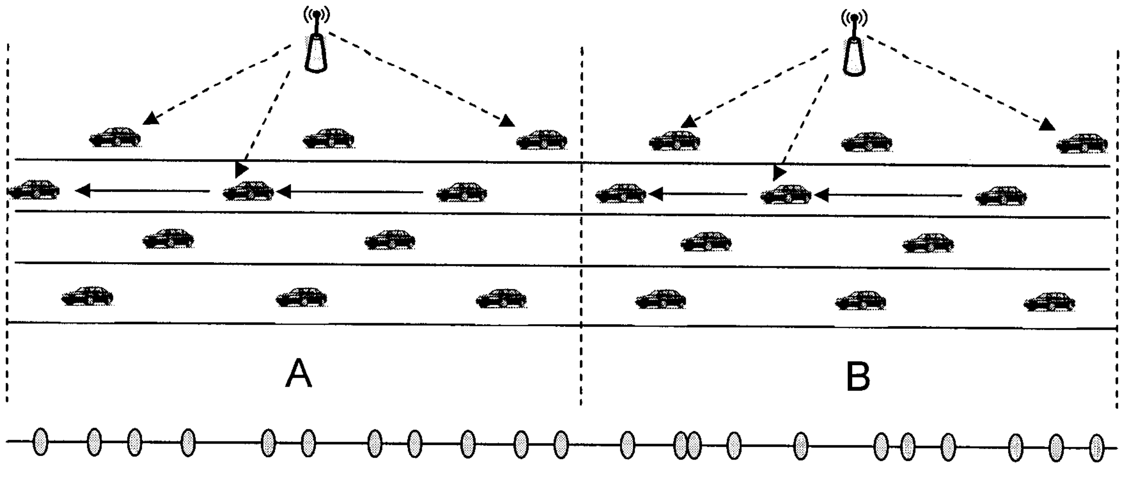


Figure 3.2 Simplification of the Problem

In Figure 3.2, the same two clusters in Figure 3.1 are simplified as two sections on a straight line, and nodes represent vehicles based on their location along the highways stretch.

3.2 Problem Definition and Greedy Algorithm

In this section, we formally define the problem of finding maximum network throughput. The selection of relaying nodes and channel assignment affects the network throughput directly. In this section, we give a formal description of the objective and constraints pertinent to the selection of relaying paths. Further, we present a greedy heuristic for finding network throughput.

3.2.1 Notations

In the following, we present the list of notations that we are going to use for this section. These notations either represent certain network parameters such as transmission range, or describe relations in the network such as interference relations between nodes. In the following sections, these notations are used to describe the greedy algorithm and the derivation of theoretical best case average. The notations are as follows:

(1) V : set of nodes.

(2) $\rho \in R_+$: transmission range, where R_+ is the set of positive real numbers. For simplicity, we assume transmission range is the same as interference range

(3) $K \in V \times V$: a set of pairs of nodes representing the source and destination of the request

(4) $R_{(s,t)}$: the set of relay nodes for the connection from s to t, $(s,t) \in K$

(5) $\theta \in Z$: number of channels, Z is the set of positive integers.

(6) $E(\rho)$: set of directed connection edges between nodes. When node a is within the transmission range of node b, then the directed connection edge $e_{ab} \in E(\rho)$, meaning node b could be the receiver of node a's transmission. Formally:

$E(\rho) = \{a,b \in V \mid d(a,b) \le \rho\}$, where $d(a,b)$ denotes the Euclidean distance between node a and node b.

(7) $N(u) = \{x \in V \mid d(x,u) \le \rho\}$: neighborhood of a node. Figure 3.3 shows the neighbors of a receiving node. Similar result can be shown for a transmitting node.

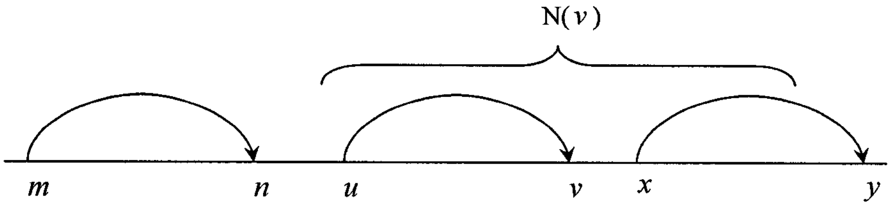


Figure 3.3 Neighborhood of Receiving Node v

In Figure 3.3, node u and node x are all neighbors of node v, because they are both transmitting nodes, and node v is a receiving node within transmission range of both of them.

(8) $I(\rho)$: interference relation. Given edge $(u,v) \in E(\rho)$, we define its interference relation with arbitrary edge (x,y) as following:

$((x,y),(u,v)) \in I(\rho)\ \mathit{iff}\ y \in N(u)\ or\ x \in N(v)$

(9) $T_{(s,t)}(v)$ - set of channel assignments for a node v in set V for a connection $(s,t) \in K$, according to the set of requests (s,t) in K.

(10) $X(s,t)$ - directed path from s to t over the edges in $E(\rho)$. We use notation $(x_i, x_{i+1}) \in X(s,t)$, $(x_i\ x_{i+1})$ is a directed edge of path $X(s,t)$, x_i, x_{i+1} are consecutive relay nodes for the connection from s to t.

3.2.2 Problem Definition

As stated in Section 3.1, we assume that the appropriate interval for relay node selection and assignment computation is given, so that we can ignore the node mobility and solve the problem as if the node distribution is static. Given this assumption, we can proceed to define the problem of finding network throughput.

Given the set of nodes V, transmission range ρ, set of source and destination pairs K, order of request π, number of available channels θ, the network throughput can be defined as the cardinality of the feasible subset M. A subset $M \subseteq K$ is feasible if

(1) we can find a relaying path $X(s,t)$ for each request (s,t) in set M, and

(2) we can find a channel assignment for all the relaying nodes so that no interference occurs.

Given a request $(s,t) \in K$, the greedy algorithm described in Section 3.2.4 computes a relaying path $X(s,t)$ if (s,t) is feasible, or rejects (s,t) if it is not feasible.

In the following paragraphs, we describe the procedure for computing a channel assignment for the relaying nodes. Given set of relay nodes for a connection (s,t) as $R_{(s,t)}$, we denote the set of corresponding channel assignments to a relay node v as $T_{(s,t)}(v)$, subject to the following constraints:

Constraint a: A node relaying for more than one request must be assigned different channels for each request,

$$\forall(s,t) \in M, \forall(p,q) \in M, \quad ((s,t) \neq (p,q) \text{ and } v \in R_{(s,t)} \cap R_{(p,q)}) \rightarrow T_{(s,t)}(v) \neq T_{(p,q)}(v)$$

One example is given in Figure 3.4. If node c is selected in two paths $X(a,b)$ and $X(g,h)$, then channel assignment for path $X(a,b)$ at node c is $T_{(a,b)}(c)$=3, similarly $T_{(g,h)}(c)$=5.

Constraint b: Any two distinct nodes u and v that are relaying packet for different or possibly the same request, if they interfere with each other, different channels must be assigned to them to avoid interference.

We use $succ_{(s,t)}(u)$ to denote the successor node (next hop node) for node u on path $X(s,t)$. Then $(u, succ_{(s,t)}(u))$ denotes the directed edge in path $X(s,t)$ that starts from node u. Similarly, we use $(v, succ_{(p,q)}(v))$ to denote the directed edge in path $X(p,q)$ that starts from node v. Then we have

$$\forall(s,t) \in M, \forall(p,q) \in M, \forall u \in R_{(s,t)}, \forall v \in R_{(p,q)}$$

$$(u \neq v \text{ and } ((u, succ_{(s,t)}(u)), (v, succ_{(p,q)}(v))) \in I(\rho) \rightarrow T_{(s,t)}(u) \neq T_{(p,q)}(v)$$

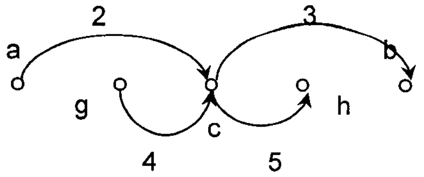


Figure 3.4 Relaying Different Paths at the Same Node

Finally, we can formally define the problem of finding the maximum network throughput as following:

> Find a subset $M \subseteq K$ of requests of maximum cardinality that can be satisfied without interfering each other. More precisely, for any request $(s,t) \in M$, there exists a path $X(s,t)$ and a channel assignment $T_{(s,t)}(v)$ for any node v in $R_{(s,t)}$, subject to Constraint a and Constraint b.

3.2.3 Offline Scheduling vs. Online Scheduling

Requests to establish connections can be submitted to the base station in different ways. In the *offline scheduling scheme*, the base station allocates certain time slots during the scheduling interval for mobile nodes to submit their requests; after all requests are collected, the base station processes all the requests. In the *online scheduling scheme*, base station allows requests to be submitted at any time during the scheduling interval. The base station processes the requests in a first-come-first-served way. These two scheduling schemes have direct impact on the network throughput.

In the online scheduling scheme, the base station has no knowledge of what request will be generated on-the-fly; the decision to accept or to reject a certain request is based on the set of requests already accepted, such that Constraints a and b in Section 3.2.2 are satisfied.

In offline scheduling scheme, the base station has the list of all the requests on hand before processing. This gives us some opportunity for optimization. The base station can decide which request to satisfy first and which requests to satisfy later. The base station does this by re-arranging the position of requests in the list, and tries to satisfy the requests one by one, from top down to the bottom of the list. The requests appearing at the beginning of the list will be assigned channels first, thus having higher priority than requests appearing later in the list. In our simulation, the base station sorts the given list K in ascending order based on the distance of the connection, thus shorter requests are given higher priorities. Comparison of the effect of these two scheduling schemes is presented in Chapter 4.

3.2.4 The Greedy Algorithm for Channel Assignment

In this section, we introduce a greedy algorithm for channel assignment for one request. Let (s,t) be the request that needs to be scheduled and M the set of requests already accepted. The algorithm in Figure 3.5 will check if one request (s,t) can be accommodated. Starting from the source node s of the request, the algorithm greedily finds the farthest neighbor node as the next hop relay node. At each relay node, the algorithm checks the channels used by its neighborhood node. If all the channels are used up, then there is no channel available for is relay node and the request is rejected. Otherwise, one unused channel is assigned to the relay node. This process is repeated until the destination node is reached. If all the relay nodes have been successfully assigned a channel, the algorithm will return the new set of feasible requests $M \cup \{(s,t)\}$; otherwise, (s,t) is rejected and set M is unchanged. The algorithm is shown in Figure 3.5.

```
Given $U(v,M)$ representing the set of channels assigned for transmission to $v$'s neighbors
procedure schedule $((s,t),M)$;
$v \rightarrow s$; /* $v$ = current relay node */
$C_{new} \leftarrow \varnothing$;
while $(v \neq t)$ do
    if $U(v,M) = \{1,...,\theta\}$, then
        /*no available channels left, reject*/
        return $M$;
  else
        /* $v$ can transmit */
        $C_{new}[v] \leftarrow min\{\{1,...,\theta\} \setminus U(v,M)\}$
    end if
    $v \leftarrow$ furthest reachable node towards $t$ from current $v$
End while
  /* request $(s,t)$ can be satisfied*/
  /*update $U(v,M)$ with $M[v]$ for all $v \in V$ */
  $M \leftarrow M \cup \{ s,t)\}$;
  return $M$
end proc
```

Figure 3.5 Greedy Channel Assignment Algorithm

3.2.5 Derivation of Expected Average Throughput

[BHA07] analyzes the general case of network throughput when vehicle distribution on the highway section is non uniform. In this scenario, node density is represented as a step function. In our thesis, we study a special case where the node distribution is uniform, and node density is constant throughout the network. Similar to the approach described in [BHA07], we derive the expected throughput of a vehicle-to-vehicle network when nodes are uniformly distributed.

Before we proceed, we first observe the following property of the radio signal interference in VANET:

Lemma 1 [BHA07]. We denote connections are *at the same direction* when packets are delivered at the same direction. In a region of length at least $2R$ (R is the transmission range), n connections in the same direction crossing this region requires at least $2n+1$ channels.

An example is shown in figure 3.6

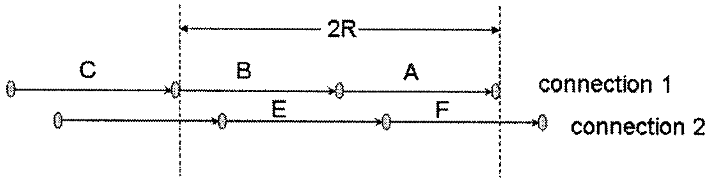


Figure 3.6 Two Connections Overlapping in Area of Length $2R$ ([BHA])

The left end and the right end of the area is shown using dotted line in Figure 3.6. Due to interference, transmission link A, B, C, E, F each need a different channel for sending and receiving, thus these two connections need 5 channels in this area to accommodate. It is obvious to see that for n connections, there needs to be $2n+1$ channels to satisfy all the connections.

Lemma 1 is for connections in one direction. However, connections can be in both directions. The network configuration giving maximum throughput is as following:

1. two connections of different directions overlap;
2. their relay nodes are positioned exactly at distance R from last hop;
3. x-coordinate of the relay nodes for one connection differ by multiples of $\frac{1}{3}R$ from the relay nodes in other direction;

in this case we can accommodate $\theta - 1$ connections using θ number of channels, as shown in Figure 3.7

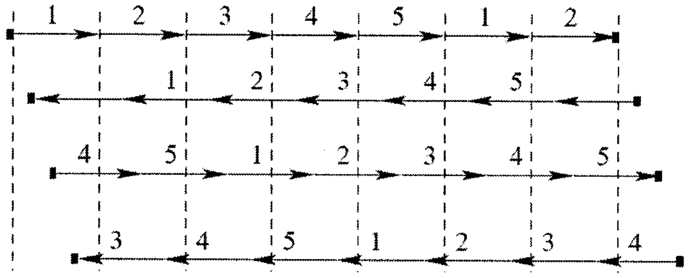


Figure 3.7 Optimal throughput in one overlapping area ([BHA07])

From Lemma 1, we know that the number of overlapping connections in one direction can not exceed $\left\lceil \frac{\theta - 1}{2} \right\rceil$. Similar to [BHA07], we assume that the node distribution is in such a way that equal number of connections in the opposite direction can always be accommodated, as shown in Figure 3.7. This assumption is for best case scenario. Based on this assumption, we expect the simulation result to be higher than average throughput.

As stated in Section 3.2.2, we simplify the vehicles in different lanes as nodes in one single line of finite length L. We denote a constant $d \in R_{+}$ as the node density throughout the network. Function $f(x)$ represents the number of feasible connections crossing each x, $x \in [0, L]$. Our purpose is to derive $f(x)$ and average length of the connections λ, so that total number of feasible connections can be computed by:

$$C_{total} = \frac{\int_0^D f(x)dx}{\lambda} \tag{1}$$

To derive function $f(x)$, first we observe that, given uniform node density along the line, the probability of having a connection across a fixed point x is the combined probability that source node is at the left side of point x while destination node is at the right side of point x, or vice versa.

$$p(x) = 2\frac{d \cdot x}{N} . \frac{d \cdot (L-x)}{N}, \quad N = \frac{L}{d} \quad \textit{total number of nodes}$$

$$= \frac{2d^2}{N^2} \cdot x \cdot (L-x) = 2\frac{x(L-x)}{L^2}, x \in [0, L] \tag{2}$$

If m connections are generated, then the expected number of connections that cross each point x on the line is given by:

$$m \cdot p(x)$$

Note that the above function is a monotonic increasing function in m. Since number of channels are limited, there is an upper bound on the number of feasible connections when m increases.

The total number of connections that can be accommodated is given by:

$$m \cdot p(x) = \theta - 1 \tag{3}$$

Replacing $p(x)$ with (2) and solving the equation, we have the point where maximum number of connections are accepted:

$$x^* = \frac{N}{2d}(1 \pm \sqrt{1 - \frac{2(\theta - 1)}{m}}) \qquad (4)$$

When $m < 2(\theta - 1)$, equation (4) has no real solution, meaning the network is not saturated, the capacity is just m.

When $m \geq 2(\theta - 1)$, $x^* = \frac{N}{2d} \cdot \alpha, \alpha = (1 \pm \sqrt{1 - \frac{2(\theta - 1)}{m}})$

We denote $x_1 = \frac{N}{2d}\alpha_1, \alpha_1 = (1 - \sqrt{1 - \frac{2(\theta - 1)}{m}})$ (5)

$$x_2 = \frac{N}{2d}\alpha_2, \alpha_2 = (1 + \sqrt{1 - \frac{2(\theta - 1)}{m}}) \qquad (6)$$

It can be easily deduced from (2) that the region between x_1 and x_2 is saturated, x_1 is the smallest x coordinate where the network is saturated, x_2 is the largest x coordinate when the network is saturated. Therefore we have:

$$f(x) = \begin{cases} m \cdot p(x) & x < x_1 \text{ or } x > x_2 \\ \hline \theta - 1 & x_1 < x < x_2 \end{cases} \qquad (7)$$

When $m \to \infty$, $x_1 \to 0$, $x_2 \to L$, and

$$f(x) \approx \theta - 1, 0 < x < L \qquad (8)$$

The average length λ of the connections generated is derived as follows. By selecting the source and destination nodes uniformly at random, the probability of generating a connection of length l, is the probability of choosing one point $x \in [0, L - l]$, and then selecting the other point at $y = x + l$; or the probability of choosing one point $x \in [l, L]$, and then selecting the other point at $y = x - l$. In the first case, the probability of selecting a node in a region $[0, L-l]$ is $\frac{d}{N} \cdot (L-l) = \frac{(L-l)}{L}$, the probability of a node locating at $y = x + l$ is $\frac{d}{N} = \frac{1}{L}$. Thus the probability for the first case is $\frac{1}{L}(L-l)$. The same result is derived for the second case. Therefore,

$$p(length = l) = 2 \cdot \frac{1}{L}(L-l) \cdot \frac{1}{L} = \frac{2}{L^2}(L-l)$$

Then the average length of all the connections generated is given by:

$$\lambda = \int_0^L l \cdot p(length = l) dl = \int_0^L l \cdot \frac{2}{L}(L-l) dl = \frac{1}{3} L \qquad (9)$$

From equation (1), (8), (9), we have

$$C_{total} = \frac{\int_0^L f(x) dx}{\lambda} = (\theta - 1) \cdot L \cdot \frac{3}{L} = 3 \cdot (\theta - 1) \qquad (10)$$

Equation (10) shows that when network is saturated, the estimated average throughput is about 3 times the available number of channels.

This equation gives us an estimation of the average network throughput in the best case scenario. We are going to evaluate the network throughput under the greedy algorithm.

3.2.6 Summary

This chapter focuses on definition and derivation of theoretical throughput. First, we give a description on the system architecture and the generic TDMA scheme at MAC layer. We then present the formal problem definition and the greedy algorithm for channel assignment. Two different scheduling heuristics, online scheduling and offline scheduling are also introduced. Finally, we present the theoretical derivation for average throughput. Specifically, when network is saturated (number of requests $m \to \infty$), the maximum network throughput is about $3(\theta - 1)$, where θ is the number of channels available.

The analysis in Section 3.2.5 gives an upper bound on the maximum number of requests that can be satisfied. The bound is tight because there is a certain pattern of node distribution that achieves it. However, this node distribution pattern is not likely to occur often in practice. So we expect to see a lower throughput in our simulation results in Chapter 4.

CHAPTER 4

PERFORMANCE EVALUATION

In this chapter, we evaluate the capacity of a vehicle-to-vehicle network under the proposed system architecture. We compare the performance of the greedy algorithm proposed in Chapter 3 to the theoretical average network throughput. We study the effect of network topology changes on throughput. The simulation is performed using NS-2 simulator.

4.1 Network Simulator 2 [NS89]

Network Simulator 2 (NS-2) is a discrete event simulator. It provides packet level simulation and tracing at different protocol layers, from the physical layer up to the application layer. It supports simulation for wired, wireless and satellite networks. NS-2 is built on top of the Tcl/Tk platform [TCL87], using C++ as the low level implementation and Tcl/OTcl (Object Tcl) for high level implementation. During the simulation, OTcl objects are created as "split objects" of C++ counterpart objects. The network structure and parameters are defined via Tcl shell (Tclsh) scripting. The purpose of the design is to avoid the time consuming C++ code recompilation when only network structure or parameters are changed.

The protocol stack for a mobile node in NS-2 is developed by the Monarch project in Carnegie Mellon University [MON92]. In this architecture, each node consists of the following layers (from bottom to top): physical layer, MAC layer, interface queue (IFQ), link layer, network layer, transport layer, and application layer.

NS-2 includes in its distribution many protocols that are ready to use. However, in the case of implementing a new protocol, we need to create the corresponding C++ class, typically by inheriting existing protocol classes. Then we need to register the new class as a new shell command in the Tcl/Tk interpreter. After this, the new protocol can be used in the Tclsh script during the simulation setup.

4.2 Simulation Setting and Performance Metric

We classify the network state into two categories based on vehicle movement and/or request distribution. One is *steady state*, which corresponds to the free-flow traffic on the highway (i.e. no car brakes, no gaps in the traffic) with a static connection distribution pattern (either evenly distributed or with certain distribution patterns). The other is *transient state*, which includes non-uniform node distribution, or dynamic connection distribution in the network.

4.2.1 Assumptions and Experimental Settings

In the simulation, we make the following assumptions:

1. As stated in Section 3.1, our scheduling period is one second, because we assume that the relative position between the nodes does not change significantly within one second. Without loss of generality, we assume that all connections last for one second for steady state simulation.
2. To highlight the effect of a transient network state, we assume that the duration of all connections is the same as the simulation time.

3. For convenience, we assume that the transmission range is the same as the interference range, as stated in Section 3.2.

In our simulation, we set up CBR (constant bit rate) sources at the application layer, and UDP protocol (User Datagram Protocol) at the transport layer. Routing at the network layer is disabled. TDMA planning is performed at the MAC layer.

4.2.2 Mobility Model and Simulation Scenarios

For the steady network state, we are interested in the network capacity in one cluster. As described in section 3.1, highways are divided into clusters of 2000 meters in span. In our test cases we simulate a highway section of 2000 meters. This highway section has 4 lanes, where each lane is 5 meters wide. To make the simulation setting realistic, we set lane 1 to be the slowest lane, with vehicles moving at an average speed of 28 meters/second (100 km/hour), lane 2 and lane 3 with an average speed of 33 meters/second (118 km/hour). Finally, lane 4 has an average speed of 38 meters/second (136 km/hour). As stated in section 3.1, our focus is on the network capacity within one cluster, therefore we arbitrarily assume that all communications are defined within this cluster.

Nodes are placed on each lane according to the average spacing, each vehicle randomly plus or minus an offset of 5 meters from other vehicles. Vehicles moving on each lane choose their speed based on the average speed of the lane, and the distance from the vehicle in the front. If the distance requires more than 1 second to traverse, the vehicle will randomly choose an acceleration rate of no more than 5 m/s^2; if the distance requires less than 1 second to traverse, the vehicle will decelerate accordingly. This speed adjustment is performed at each second. Transient state mobility patterns are described in Section 4.3.2. We classify the simulation scenarios into different test cases as shown in Table 4.1. In the table, the node distribution column describes how the nodes are placed on the highway lanes and the connection distribution column describes how the source and destination nodes are selected. Detailed description will be presented in the corresponding sections.

Scenario	Node distribution	Connection distribution
Steady Network State	Uniformly distributed	Uniformly distributed
Hot Spot in the Network	Uniformly distributed	Within certain area nodes tend to establish "local" connections
Transient Network State		
Packs in Networks	Uniformly distributed	Intra-/inter-pack connections and background connections
Stop-and-go Waves	Non-uniform	Uniformly distributed
Gap	Gap in the traffic flow	Uniformly distributed

Table 4.1 Classification of Network Scenarios

4.2.3 Performance Metrics and Simulation Parameters

The network throughput is one of the most important performance metrics in network designing and planning. The focus of this thesis is on network throughput, defined by the number of requests being accepted by the scheduler.

The parameters affecting network throughput are: number of channels, transmission range, total number of requests arrived per second, and node density. Different simulation scenarios may use different numeric values of these parameters; we list the values for these parameters in corresponding sections.

4.3 Discussion of Results

4.3.1 Average Network Performance

In this simulation scenario, we set the range of a highway section to 2000 meters, as stated in Section 4.2.3. We perform a simulation using the following parameter settings shown in Table 4.2:

Parameter	**Value**
Transmission range (meter)	50, 100, 150, 200
Total requests per second	70, 90, 110, 130, 150, 170, 190
Number of nodes	244, 287, 352, 455
Number of Channels	36, 48, 60

Table 4.2 Simulation Parameters for Average Performance Case

The choice for the number of nodes of 244, 287, 352, 455, corresponds to inter-vehicle spacing of 30 meters, 25 meters, 20 meters and 15 meters, respectively.

Note that in our simulation, vehicle speed is related to vehicle spacing, this is because in real world scenarios, vehicles normally keep about one second distance at the current speed from the vehicle in the front. Higher node density means smaller inter-vehicle spacing, which in turn means lower vehicle moving speed.

Unless otherwise specified, communication requests are generated by randomly choosing one node as the source node, and randomly choosing another node as the destination node. A request list consists of all the requests. Relay node selection and channel assignment for these requests are performed periodically. At each second the base station examines the requests for establishing connections, performs channel assignment computation, and then the result is broadcast to the vehicles in the cluster. Simulations in this section are all for the steady state case, and connections are set to last for one second. Each simulation is run for 100 seconds continuously. Reported results are averaged over 10 repeated experiments.

4.3.1.1 Effect of Varying Request Intensity

Intuitively, increasing the number of requests arriving per second increases the total number of accepted requests, until the network is saturated. For each given transmission range and node density, we vary the total number of requests per second using the following values: 70, 90, 110, 130, 150, 170, 190. The base station uses on-line scheduling and off-line shortest-distance-first scheduling defined in Section 3.2.4. Total number of channels available is 36. Requests are generated by randomly choosing a node as the source node, and another node as the destination node. The probability of generating a request of certain length is given in Section 3.2.5. In the simulation, we classify connections into two categories: connections with no more than 2 hops (referred to as short connections and denoted as "1&2 hops" in the performance figures), and connections with 3 or more hops (referred to as long connections, denoted as "3+ hops" in the figures). The results are shown in Figure 4.1.

From the simulation result, and as expected, we can see that offline scheduling out-performs online scheduling in terms of total requests accepted, as shown in Figure 4.1 (a) and (d). Through the breakdown charts for different hop distances in Figure 4.1 (c) and 4.1 (f), we can see that, for the given transmission range, the offline scheduling algorithm admits more 1&2 hops connections. Similarly, Figures 4.1 (b) and 4.1 (e) show that the

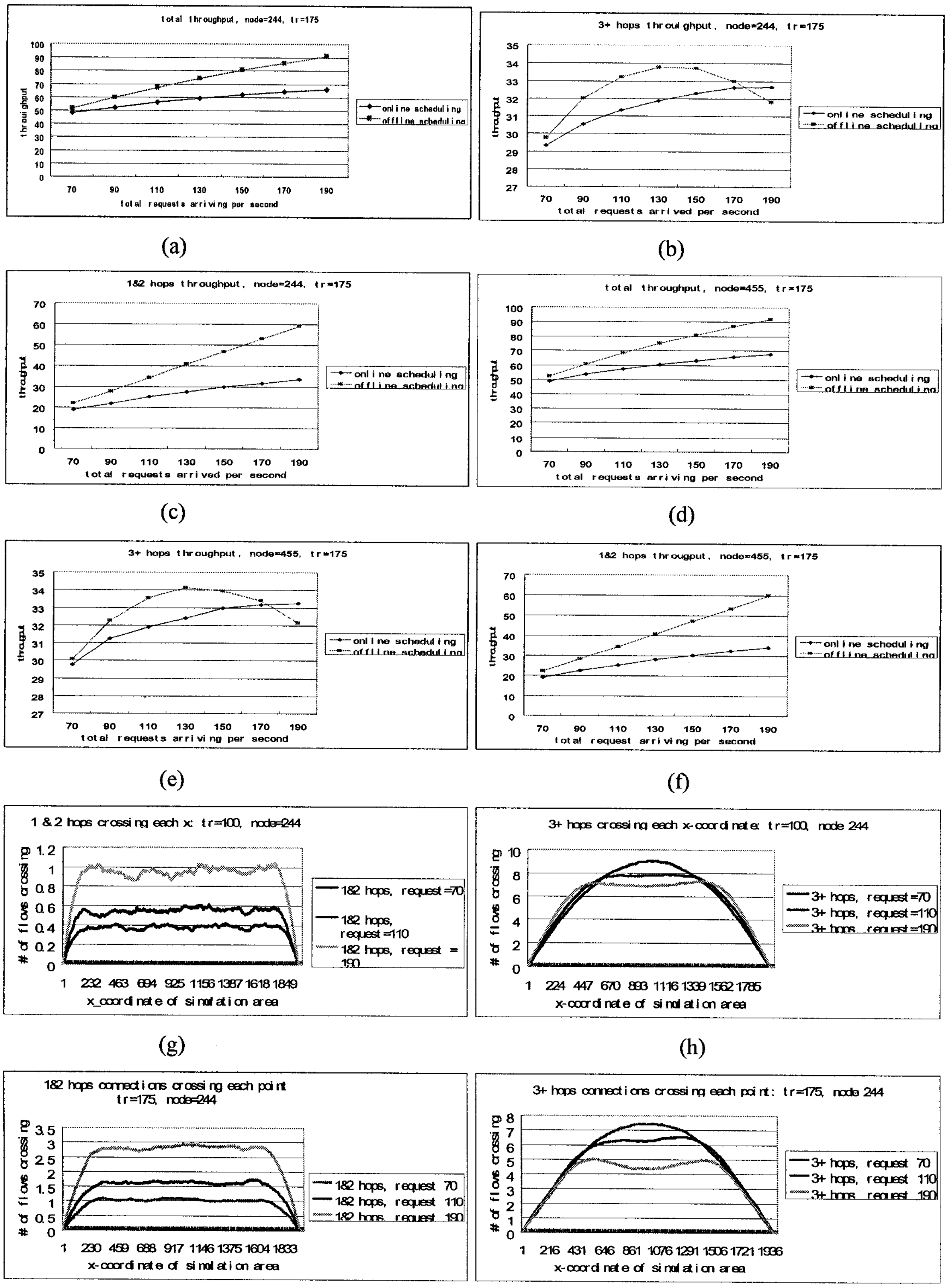


Figure 4.1 Effect of Varying Request Intensity.

offline scheduling algorithm admits more connections with 3+ hops. This is due to the fact the offline scheduling places shorter requests ahead of longer requests in the request list, thus give higher priority to shorter requests, causing more of the longer requests to be rejected. In this way, the network channel reusability is improved. Note that, as the number of requests increases, the number of long connections (3+ hops) increases, and as the network becomes saturated, the number of long connections admitted levels off, and then begins to decrease, as shown in Figure 4.1 (b) and (e). This phenomenon happens in both of the offline and online scheduling schemes. However, because offline scheduling tries to satisfy all the short requests before long requests can be scheduled, the number of admitted long connections decreases more rapidly in offline scheduling.

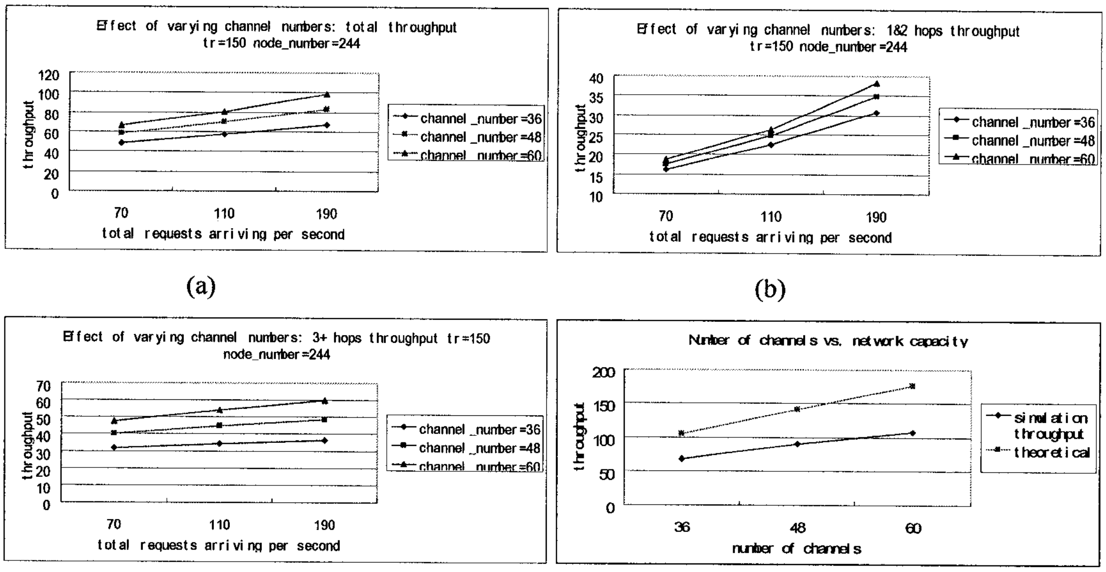
To measure the spatial distribution of the requests scheduled, we need to see the number of long and short connections crossing each node. In the simulation, we counted the average number of short and long connections crossing each x-coordinate of the simulation highway using the on-line scheduling scheme. As shown in Figure 4.1 (g) and Figure 4.1 (i), as the number of total requests increases, more nodes have short connections crossing them, and more short connections are crossing each node. However, as the number of requests decreases, the average number of long connections passing each coordinate decreases or stays the same, as shown in Figure 4.1 (h) and Figure 4.1 (j).

According to the discussion in Section 3.2.5, when the number of requests $m < 2(\theta - 1)$ (θ is the number of channels available), the network is not saturated. As m increases over $2(\theta-1)$, requests begin to be rejected on average. Our simulation results illustrate the effect when there are 36 channels available. Figure 4.1 (h) and Figure 4.1 (j) show that when request arrival rate is less than 70 requests/second, the network is not saturated. When request arrival rate is at 110 requests/second, network is moderately saturated, and some long requests are rejected, as shown by the flatten curve in the middle of the chart. When request arrival rate is at 190 requests/second, the network is heavily overloaded, and more long request are rejected. We will use this observation in the following simulations.

4.3.1.2 Effect of Number of Channels

Increasing the available channels will monotonically increase the throughput, both for the short requests and long requests, as demonstrated in Figure 4.2 and is quite straightforward. In a TDMA MAC protocol, given a fixed number of frequencies, the only way to increase the number of channels is to increase the number of time slots. Of course, increasing the number of time slots in a frequency band decreases the data throughput for each connection because of the reduction in capacity for one time slot. In the following, we compare the result with the theoretical estimation in Chapter 3.

As shown in Section 4.3.1.1, when the network is saturated (total request arrival rate around 190/second), the total number of accepted requests is around 70 when there are 36 channels available and random scheduling is used. The theoretical average expected throughput, under the same condition, is $3\times(\theta-1)=105$. The simulation result is 30% lower than our theoretical estimation. We repeated the simulation using channel numbers 36, 48 and 60. In each simulation, we increased the request intensity until the network is totally saturated and network throughput stopped increasing. The results are shown in Figure 4.2 (d) and Table 4.3. We can see that, the simulation results are about 30% lower than our theoretical estimation.



(a) (b)

(c) (d)

Figure 4.2 Effect of Varying Number of Channels

Number of Channels	**Theoretical**	**Simulation Throughput**	**Request Intensity**
36	105	67	190
48	141	90	254
60	177	107	320

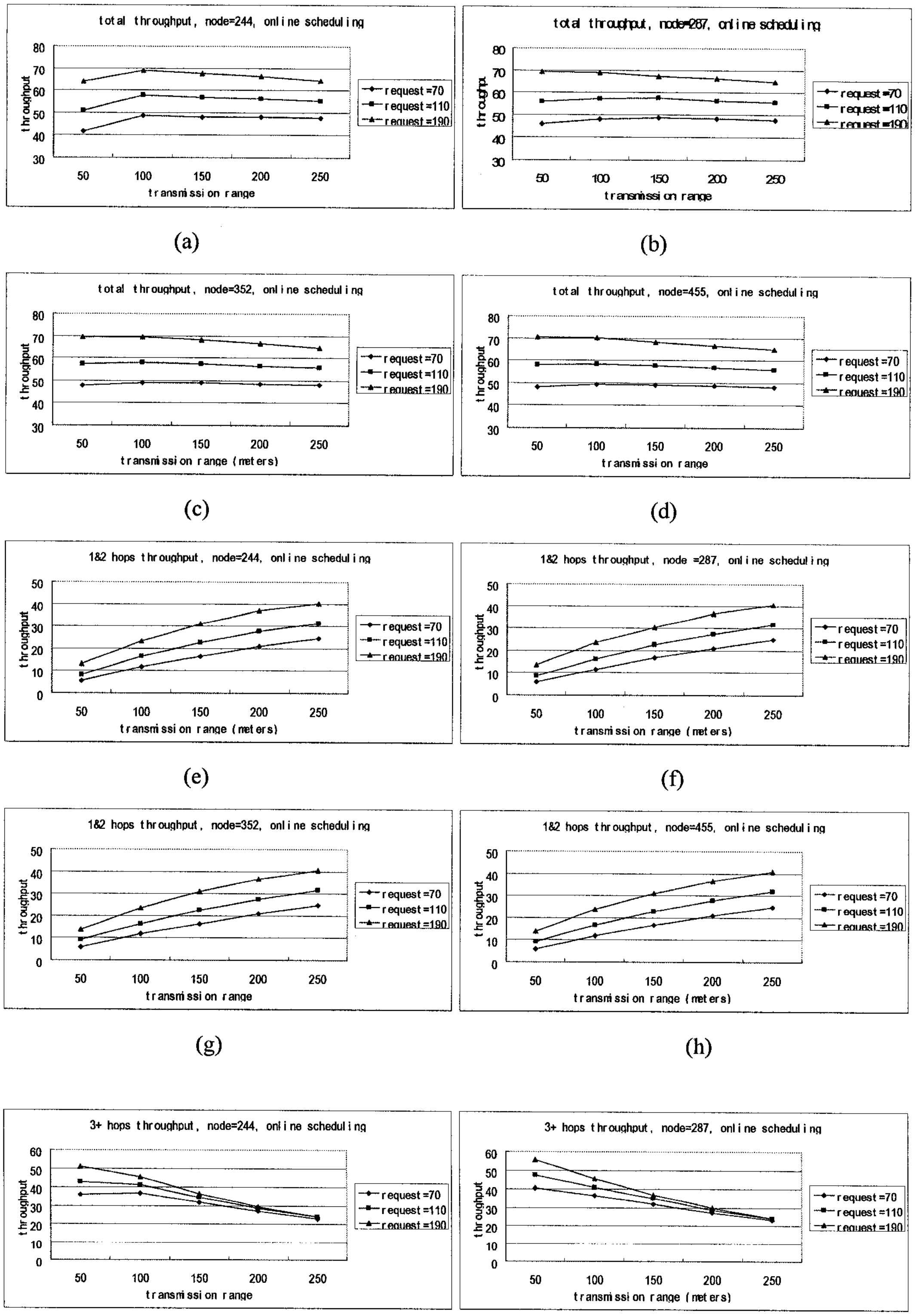
Table 4.3 Number of Channels vs. Network Capacity

As discussed in Chapter 3, this difference is due to the assumption we made when estimating the maximal number of connections crossing each x coordinate along the line. In the theoretical analysis, we assumed that all the connections are distributed in such a way that connections in both directions can share the same channels; also, we assumed that there are sufficiently many nodes, so we can always find a relay node located exactly at distance R (R is the transmission range), thus the interference caused by relay nodes are minimal. In our simulation, because source and destination nodes are randomly chosen, location of source and destination nodes may not be ideal, therefore, connections in both directions are unlikely to share the same channels, resulting in lower network throughput. Moreover, in the simulation we may often choose a closer node as relay node, causing greater interference, leading to reduced network throughput.

4.3.1.3 Effect of Varying Transmission Range and Node Density

Transmission range is an important parameter for multi-hop network throughput, because multi-hop network throughput depends on spatial channel re-usability. Generally speaking, given a node density and a set of source-destination pairs, a longer transmission range means requests can be satisfied by fewer hops, improving the spatial channel re-usability. However, longer transmission range also leads to wider interference range, reducing spatial channel re-usability. Although a shorter transmission range results in a smaller interference range, more hops are needed to link the source-destination pairs, therefore a shorter transmission range may actually reduce the spatial channel re-usability. The final network throughput is the result of all these conflicting factors.

Figure 4.3 shows the effect of different transmission ranges on network throughput. We used the following values of the transmission range: 50, 100, 150, 200, and 250 meters. Three different values for request intensity are selected: 70 (network is not saturated), 110 (network is moderately saturated) and 190 (network is overloaded).



(a) (b)

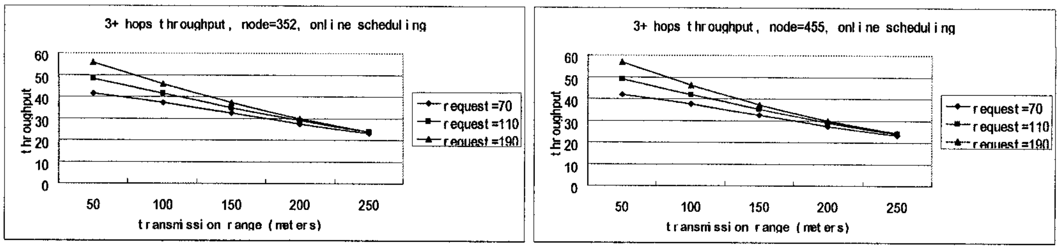
(c) (d)

(e) (f)

(g) (h)

(i) (j)

Figure 4.3 Effect of Varying Transmission ranges (1)

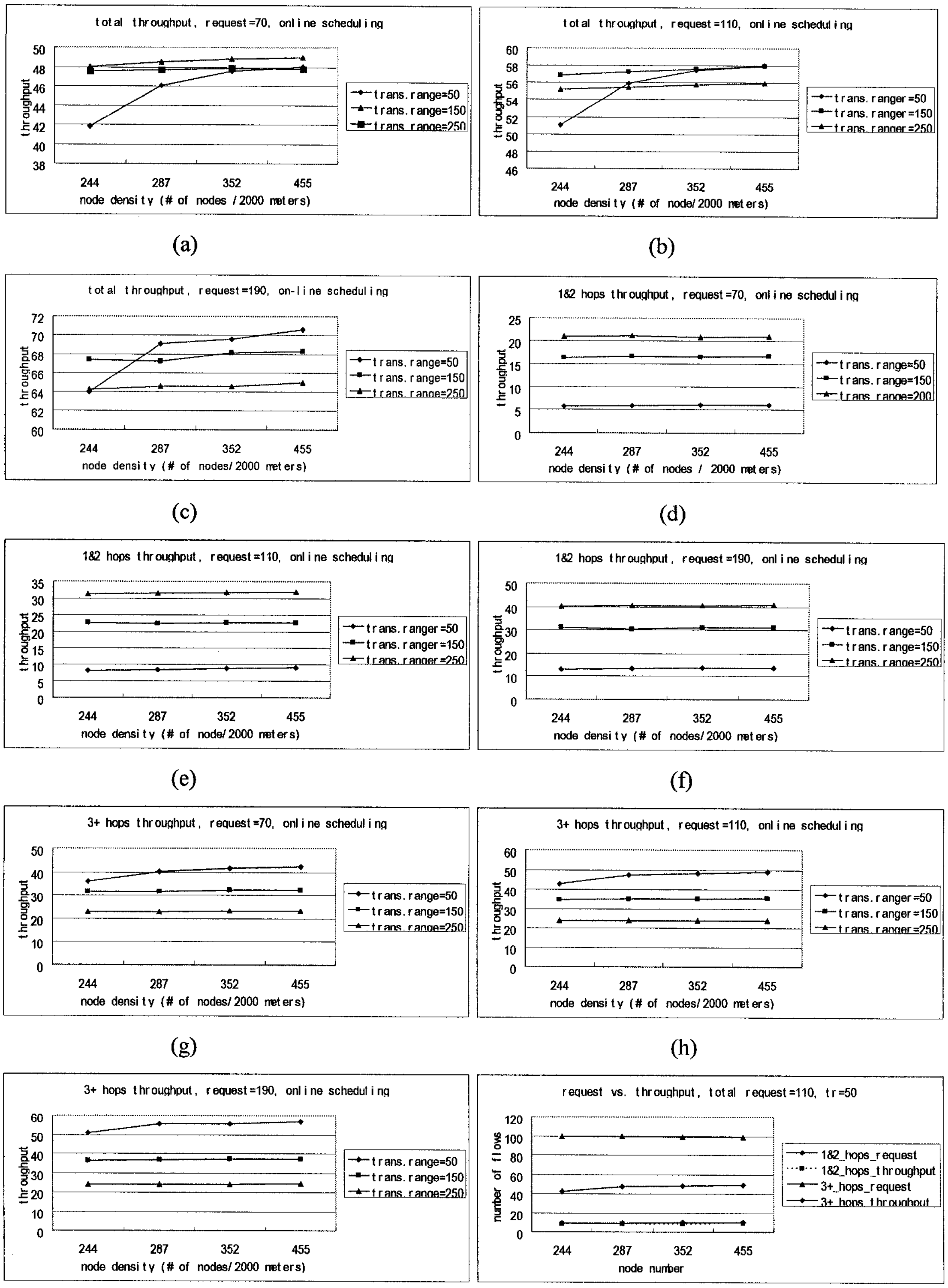


(k) (l)

Figure 4.3 Effect of Varying Transmission Ranges (2)

From Figure 4.3, we can see that node density is an important factor when the transmission range is comparable to the average inter-node spacing. When node number is fixed at 244, there is a 10-25% increase in network throughput when transmission range is increased from 50 to 100 meters, see Figure 4.3 (a). This is because, when the transmission range increases from 50 meters to 100 meters, some of the multi-hop connections become 1 hop or 2 hops connections, thus the network spatial channel reusability is improved. Although increasing the transmission range decreases network throughput due to increased interference range, the savings from decreasing 3+ hop connections is dominating. As shown in Figure 4.3 (c), (f), (g), and (h), 1&2 hop connections contribute to the increase of total throughput.

One similar but different case is shown in Figure 4.4. In Figure 4.4, only the node density is changed, the transmission range remains the same. For transmission range of 50 meters, when node density changes from 244 nodes to 287 nodes, the network throughput increases by about 10%, as shown in Figures 4.4 (a) and (b). In this case, the number of 1 & 2 hop connections as well as 3+ hop connections do not change, because the transmission range is the same. However, as the node density increases, a better relay node (a farther relay node)



(a) (b)

(c) (d)

(e) (f)

(g) (h)

(i) (j)

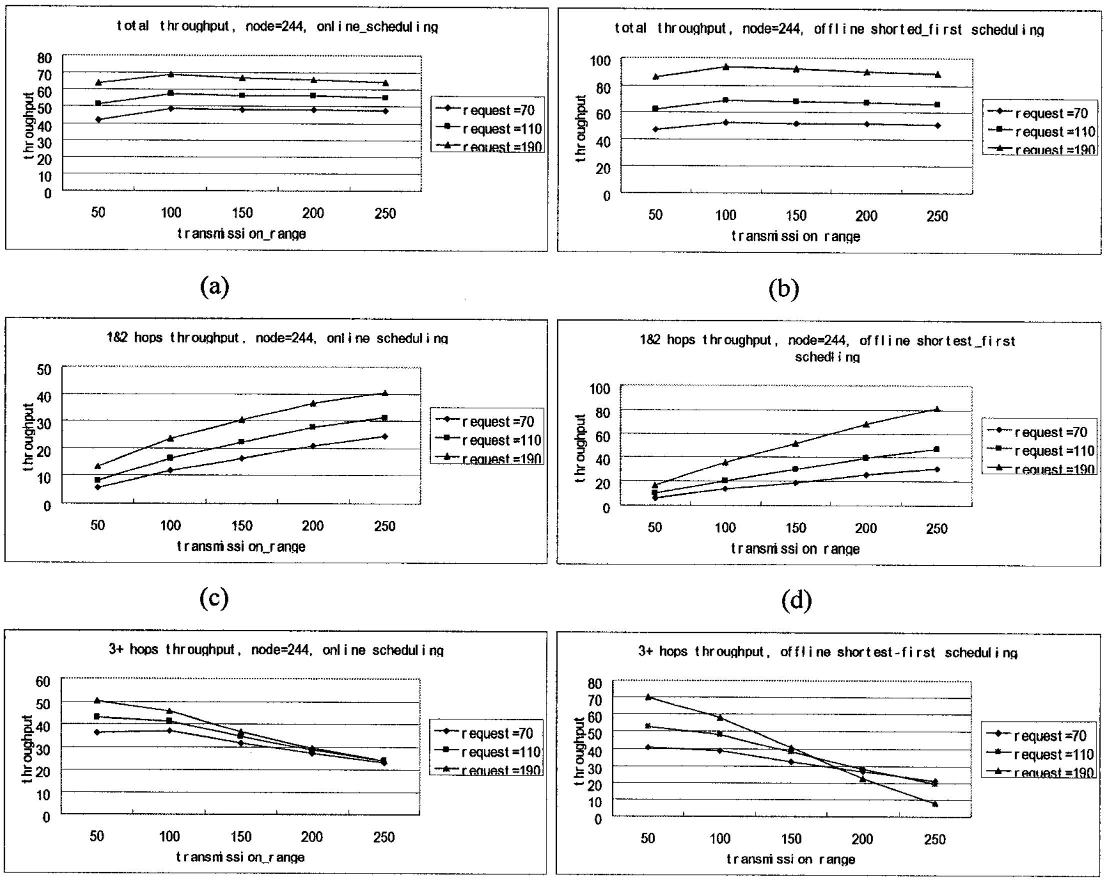
Figure 4.4 Effect of Varying Node Density.

can be selected for multi hop connections, reducing the wireless signal overlapping area created by closer relay node along the multi-hop connection. This increases spatial channel re-usability. Therefore we can see that the added multi-hop connections contribute to the total increase of throughput, as shown in Figures 4.4 (g), (h) and (i). Figure 4.4 (j) compares the number of requests and the throughput for short and long connections. We can see that, as node density changes, the throughput for short requests does not change because all short requests have been already accepted. However, the throughput for long requests increases, contributing to the total throughput increase.

If the average spacing between nodes is much smaller than the transmission range, node density does not affect throughput significantly. This effect is also shown in the charts in Figure 4.4. In our simulation, when the node density is above 287, as the node density increases, network throughput remains unchanged with different transmission ranges.

At a high node density, a shorter transmission range outperforms a longer transmission range when the network is saturated, as shown in Figure 4.4 (c). In this case, the negative effect of a long interference range outweighs the positive effect of fewer intermediate hops, and network throughput decreases.

A comparison between online scheduling and offline scheduling is shown in Figure 4.5. We can see that offline shortest first scheduling significantly outperforms online scheduling, as shown in Figures 4.5 (a) and (b). This is due to the fact that short connections are always satisfied first in offline scheduling, resulting in fewer long connections than in online scheduling. As the result, Figure 4.5 (f) shows that the number of accepted 3+ hop connections drops faster in offline scheduling than in online scheduling, especially when the network is heavily loaded.



(a) (b)

(c) (d)

(e) (f)

Figure 4.5 Effect of Varying Transmission Range - Comparison between Online and Offline Scheduling

4.3.1.4 HotSpots In the Network

Communication hotspots can exist in the network, either due to a base station is placed on the highway to interact with the vehicles in its vicinity, or when a base station with Internet backbone is actively using the neighboring vehicles to relay data flow to other nodes. See Figure 4.6.

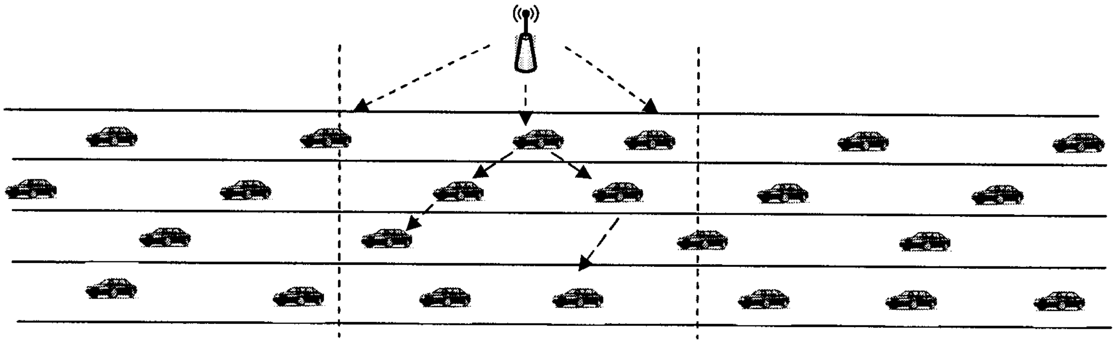


Figure 4.6 Hotspot Area in the Network

In our simulation setting, vehicles are uniformly distributed along the highway section of 2000 meters. The hotspot area is between 900 meters to 1100 meters. In our three test scenarios, 30%, 50% or 70% of the total connections arriving at every second are within this section. This setting effectively creates a hotspot within the aforementioned region, and all connections inside this hotspot are 1 hop or two hops in distance. Because hotspots in the network is basically a connection distribution issue, in the simulation we fixed the transmission range at 150 meters and node number as 287. The effect of online and offline scheduling is compared. Simulation results are shown in Figure 4.7.

The existence of a hotspot in the network reduces the channel availability in the designated hot spot area, thus reducing the number of long connections that run from one side to the other side of the hotspot. This effect is not obvious when we are using online scheduling, as shown in Figure 4.7 (f), however the effect is significant when offline scheduling is used, as shown in Figure 4.7 (i). When the long connections are rejected by the scheduler, additional channels can be used by short connections in other part of the network, and the network throughput increases accordingly. Simulation results show that the network throughput is generally higher when only 30% of the total connections are inside the hotspot, as shown in Figure 4.7 (a).

On the other hand, as a higher percentage of connections are designated inside the hotspot area, fewer connections are left outside of the hotspot area. One obvious fact is that, in this case the network throughput mainly depends on the number of requests accepted in the hotspot area. This typically results in lower network throughput compared to uniformly distributed connections, as shown in Figure 4.7 when the percentage of requests inside the hotspot area is at 50% or 70%.

Different scheduling schemes (as described in Section 3.2.4) have a significant impact on network throughput in a hotspot scenario, because connections inside a hotspot are all 1 hop or 2 hops in length. These connections get higher priority in the offline scheduling scheme. As shown in Figure 4.7 (g), offline scheduling outperforms online scheduling here as well. In the offline scheduling scheme, the number of accepted connections inside a hotspot increases significantly with the number of requests, essentially saturating the hot spot area and blocking the connections crossing the hotspot area. Because more long distance connections are rejected, spatial channel reusability is improved. The effect is that more channels can be used on requests outside the hotspot area, thereby increasing the number of accepted connections outside hotspot area. The combined effect is an increased total number of accepted connections in the offline scheduling scheme.

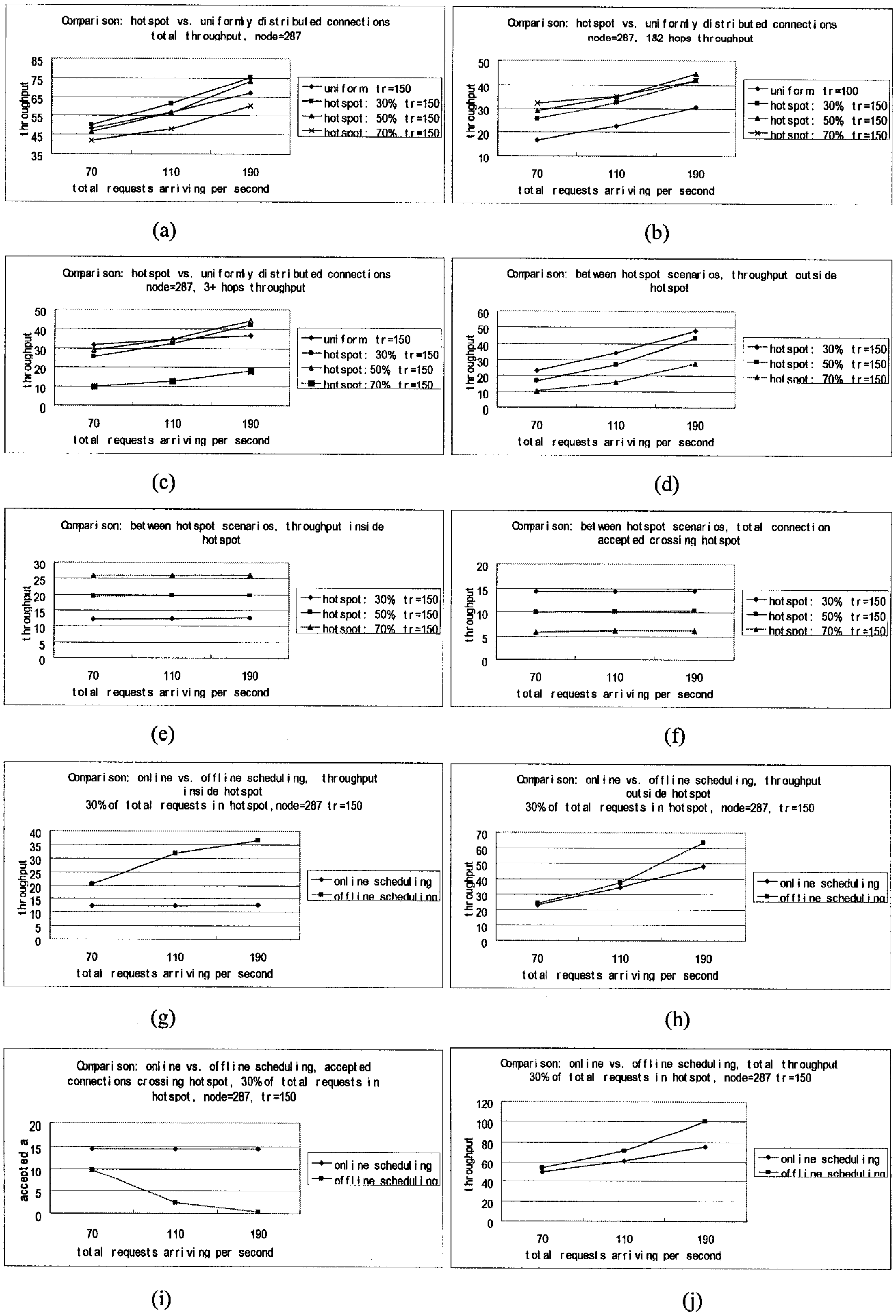


Figure 4.7 Effect of Hotspot

4.3.2 Transient State Network Dynamics

In the previous section, we simulated the scenario when highway vehicle traffic is a free flow. However, in many cases, vehicles moving on highways have special mobility patterns and cause transient states that affect network performance such as network throughput. In the following sections, we investigate the network performance variations during three common types of transient states in the vehicle-to-vehicle network.

To highlight the network throughput change over time, in the simulation we set the time span of all the requests to last throughout the whole simulation.

4.3.2.1 Merging Vehicle Packs

Some vehicles tend to travel in packs on highways. For example, heavy trucks often team up and follow each other on the highway to reduce wind drag. In this simulation, we demonstrate the effects of vehicle packs in the traffic, especially when one pack moves closer and overtakes the other pack. We set up two packs of vehicles. Each pack has 4 vehicles, and all 4 vehicles are located within the transmission range of each other. In other words, intra-pack communications are all one hop in length. In our simulation scenario, the two packs have a non-zero relative speed. One pack is on Lane 1, and the other pack is on Lane 4. At the beginning of the simulation, the distance between the two packs is greater than the transmission range. The two packs then move closer to each other, until they finally overlap. See Figure 4.8.

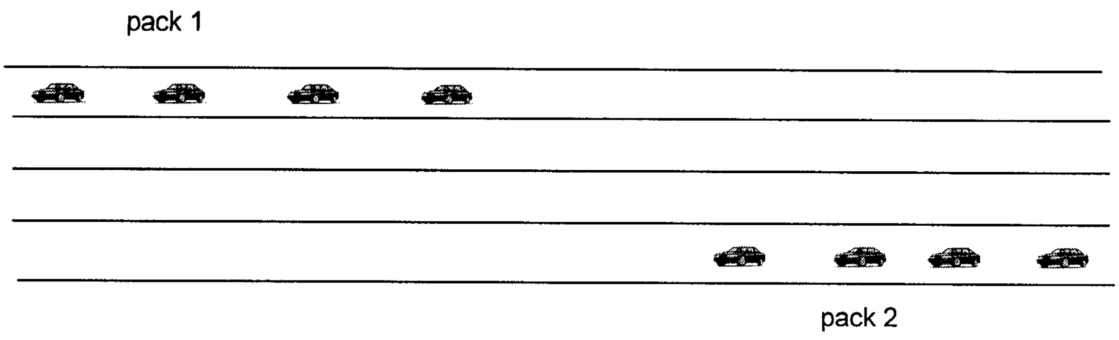
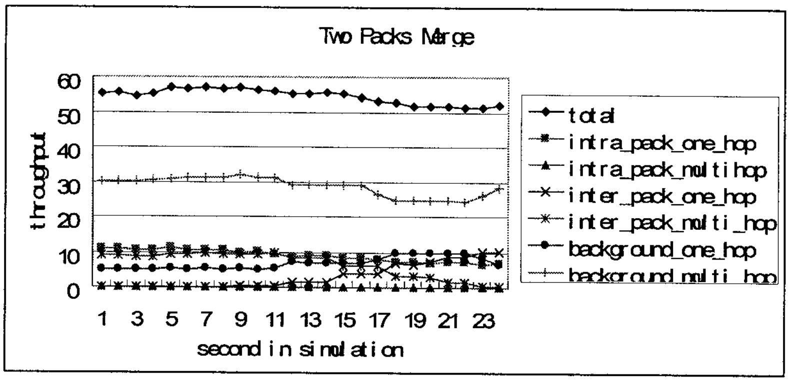


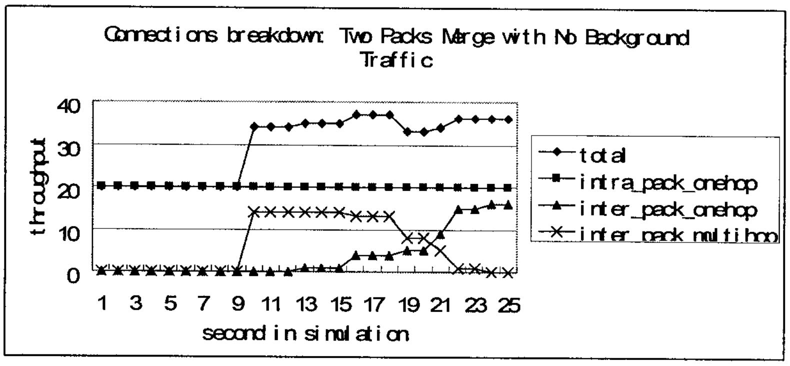
Figure 4.8 Packs in Traffic (no background traffic is shown)

We simulate two cases, one is two packs with background vehicle traffic, and one is two packs with no background. In the two packs with background vehicle traffic scenario, we use 121 vehicles uniformly distributed on the simulation highway section, two packs of vehicles are set up among the vehicles. Each pack contains 4 nodes. We setup 121 connection requests as follows: at the beginning of the simulation, 10 connections are setup inside each pack (intra-cluster connections), and 20 connections are setup between the two packs (inter-cluster connections). The rest of the connections are set up between other nodes as background data traffic. The scheduling algorithm is online scheduling. The whole simulation runs for 25 seconds. The simulation is repeated for 100 times and the average is taken. The result is shown in Figure 4.9 (a).

In the case without background traffic, we remove the background vehicles and connections, using only the vehicles and connections for the packs. The result is shown in Figure 4.9 (b).Separating the admitted requests by the number of hops on each connection, we can see that the number of inter-cluster one hop increases significantly when two packs merge, while inter-cluster multi hop connections drops to zero.



(a) with background



(b) without background

Figure 4.9 Merge of Two Packs

The effect of merging vehicle packs is that it causes dynamic changes in the amount of short and long connections in the network, thus network throughput changes accordingly. When packs are outside of transmission range of each other, the inter-pack connections are multihop long connections, occupying channels in the network area between these two packs. When two packs merge, these long connections become short, one hop connections limited inside the pack, thus freeing up channels for background connections. When two packs split and leave each other, this process is reversed.

4.3.2.2 Stop-and-go Waves

One frequent driving pattern in highway traffic is the stop-and-go waves. This event is typically triggered by some vehicle braking for certain events, for example, when a deer is running across the highway, or a strip of slippery road surface is observed ahead, or a slower vehicle just changes lane. Although the first vehicle in the lane only brakes for approximately one second and then accelerates, the vehicles after them have to brake accordingly because every vehicle needs to maintain a certain safety distance. Thus a stop-and-go wave is created and ripples downstream in the highway traffic. This effect is shown in Figure 4.10. In some circumstances, the stop-and-go wave can escalate into a traffic jam stretching several kilometers downstream. Slight to moderate stop-and-go waves happen frequently in highway traffic. It is important to find out whether our network architecture is sensitive to such network changes.

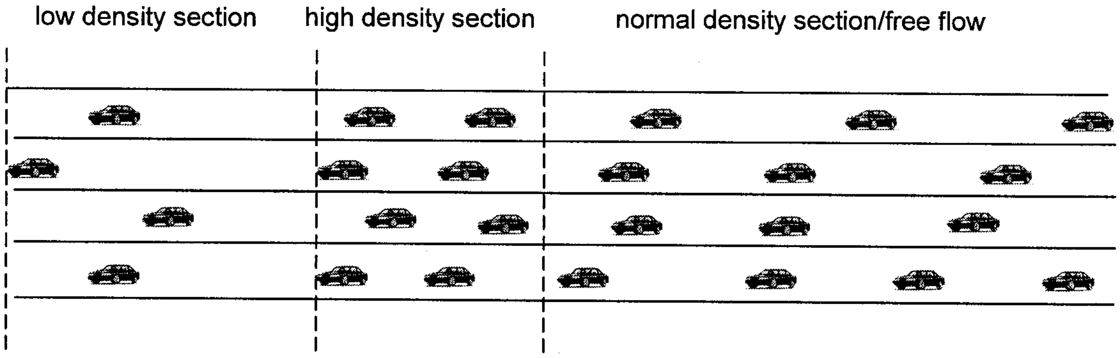
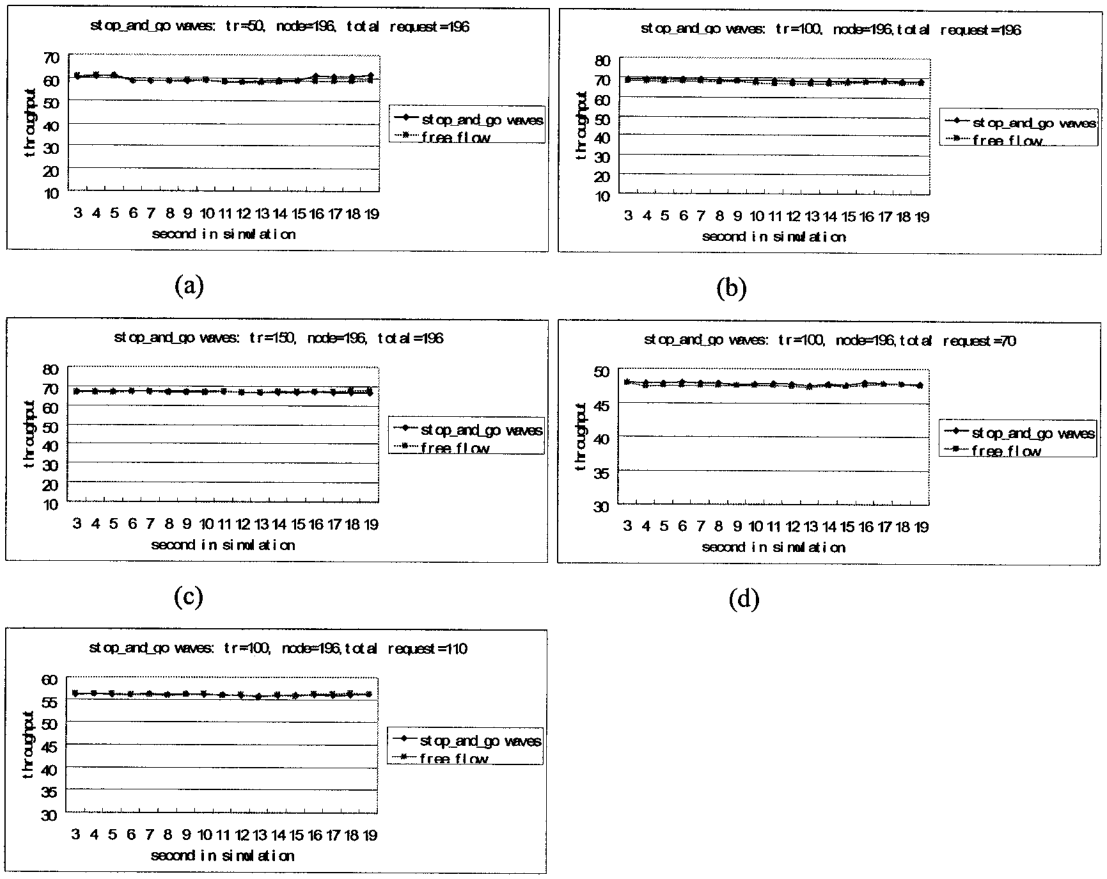


Figure 4.10 Stop-and-Go Waves

Stop-and-go waves essentially create a non-uniform distribution of nodes. Specifically, they create highway sections with different node density, as shown in Figure 4.10. One has higher node density because of breaking, and the other has a sparse node distribution because of the acceleration. The effect of this special node distribution pattern on network throughput is the result of many factors working together. For example, higher node density helps to select a farther relay node; however, if source-destination pairs are distributed uniformly across the nodes, higher node density will result in a higher density of transmitting nodes competing for local transmission media. Sparsely distributed nodes help in reducing local competition. However, the relay nodes may not be located at the farthest position, thus increasing the relay signal overlapping area and reducing spatial channel re-usability.



(a) (b) (c) (d) (e)

Figure 4.11 Effect of Stop-and-Go Waves

In our simulation, we have 196 nodes uniformly distributed across the simulation area, and 196 connections are setup among these vehicles. At simulation seconds 2 to 4 and seconds 7 to 9, 4 leading cars at each lane break for 2 seconds, and then accelerate back to normal speed. Simulation results show that 2 seconds after the first breaking, about 10 vehicles are involved in the “wave” that ripples through the traffic. The simulation lasts for 20 seconds, and is repeated 100 times. Our simulation is performed using 3 different transmission range settings: 50, 100, and 150 meters. Simulation results are shown in Figure 4.11 (a), (b), and (c). Further, under the 100 meter transmission range, we perform the simulation using the following values of request intensity: 70, 110, and 196. Simulation results are shown in Figure 4.11 (b), (d) and (e). The results are compared with free flow traffic under the same setting.

Through the simulation results, we observe that slight stop-and-go waves have only marginal impact on network throughput when the transmission range is at 50 meters. As the transmission range is increased, the network throughput basically is not affected by slight stop-and-go waves in the traffic. The simulation demonstrates that network throughput in the system architecture is resilient to slight changes in node distributions.

4.3.2.3 Gaps in Flow

Gaps are not uncommon in highway traffic. Here we simulate the effect of closing gaps. The simulation scenario assumes a gap exists in the traffic flow, with the vehicle traffic thus divided into two halves, as shown in Figure 4.12.

In our simulation, vehicles in the front half move slower than those in the back half, due to some road conditions. The back half of the traffic soon catches up with the front half, and the gap diminishes. In our simulation, we set up 186 nodes with 186 requests. We simulated

3 different distances of gaps: 80, 90, and 110 meters, with the transmission range set to 100. The results are shown in Figure 4.13.

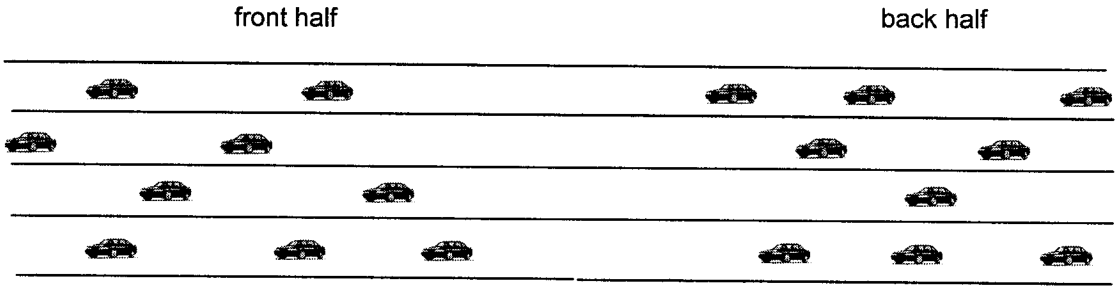
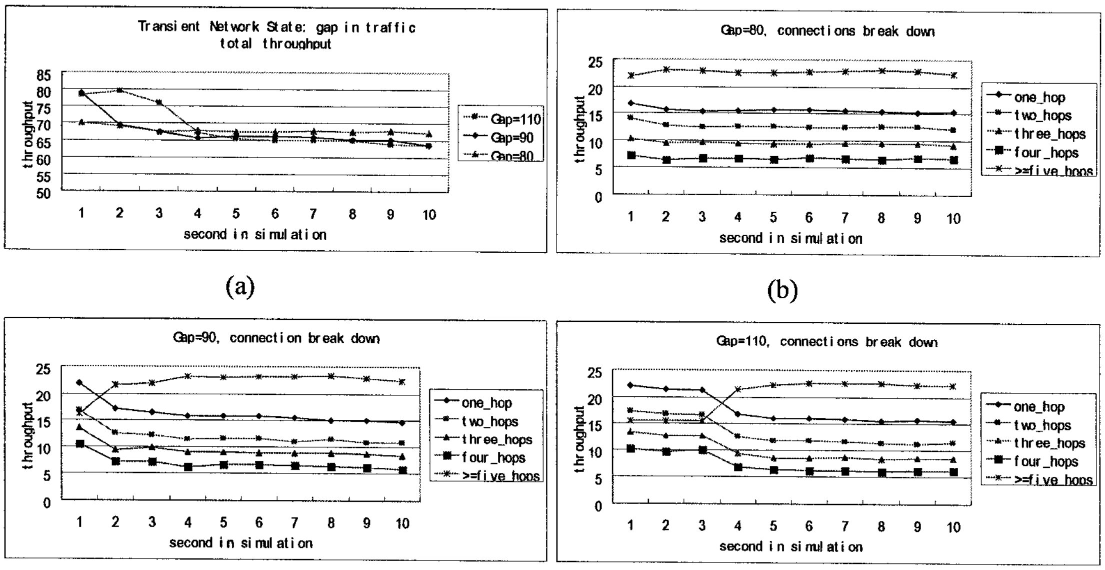


Figure 4.12 Gap in the Highway Traffic

Essentially, the existence of gaps in traffic causes near relay nodes to be selected. If the distance of the gap is about the same as the transmission range, then the vehicle at the edge of the gap is always chosen to be the relay node, even if the source is very close to the relay node. This could cause serious transmission signal overlapping, decreasing the channel reusability of the network and reducing the total network throughput. This effect is shown in Figure 4.13 (a), (b), and (c).



(a) (b)

(c) (d)

Figure 4.13 Effect of Gap in Traffic

Also from Figure 4.13 (a), we can see that if the gap distance is longer than the transmission range, the network is essentially disconnected. This effect reduces the number of long range requests between the two halves of the network, leaving room for other shorter connections within each half. Thus the total network throughput increases. However, when the two halves of the network approach each other and establish connections between them, long connections can be established between them. This reduces the number of shorter connections inside each half and the network throughput is diminished. This effect is shown in Figure 4.13 (d).

4.4 Summary

In this chapter, we conducted a performance evaluation of a vehicle-to-vehicle network using NS-2 simulation. We identified four network parameters that affect network throughput: transmission range, total request arrival rate, node density, and number of available channels. Using a greedy channel assignment algorithm, we conducted simulations for steady state and transient network state, and compared the effect of online scheduling and offline scheduling algorithms.

Our simulation results show that the greedy channel assignment algorithm performs at about 70% of the theoretical average best case throughput. In our mathematical derivation of system throughput, we used the assumption that all source and destination pairs are always placed at specific locations, therefore, the theoretical result is expected to result in a higher value than the actual average throughput. Our future work should include deriving a better theoretical average throughput.

Our simulations show that node density affects network throughput only when average inter-node spacing is comparable with transmission range, as shown in Figure 4.3 where the transmission range is 50 meters and number of nodes is 244. When the inter-node spacing is comparable with the transmission range, the radio signal overlapping area created by the relay nodes is high (because we assume that all nodes have omni-directional antenna), which reduces network capacity. As the node density increases, better relay nodes can be selected, decreasing the radio signal overlapping area, and increasing the network capacity. Our conclusion is that node transmission range should not be too small. However, transmission range should not be too large, either. As shown in Figure 4.4, when the transmission range is greater than 100 meters, network throughput decreases as transmission range increases. This is due to the increased interference range of each transmitting node. Our simulation results show that network throughput is highest when transmission range is between 100 and 150 meters.

Simulation results also show that offline scheduling significantly outperforms online scheduling, as shown in Figure 4.4. Long range (multi-hop) connections decrease network capacity more than single hop or two hops connections. Offline scheduling tries to satisfy short range connections first, while online scheduling treats long range and short range connections equally. Given a fixed number of channels available, offline scheduling will accept more connections.

It is shown that the greedy channel assignment algorithm is quite resilient to minor disruptions in node distribution, as shown in the stop-and-go wave simulation. On average, a minor change in node density does not affect the selection of the next hop node, thus creating the same interference inside the network. Therefore network throughput remains approximately the same.

Our simulations also show the significant impact of a gap in traffic. A gap in the network will force some connections to choose a closer relay node, and this kind of relay nodes creates large radio signal overlapping areas, with the consequence of saturating the area near the edge of the gap. The effect is that long connections across the gap are rejected, making room for connections inside each part of network. Gaps in the traffic lead to higher network throughput by partitioning the network and localizing the connections.

Chapter 5

Conclusions and Future Work

5.1 Summary

In this thesis, we studied the problem of providing high speed wireless connection to vehicles on highways using vehicle-to-vehicle communication. In recent years, many proposals appeared in the literature addressing data propagation in vehicular ad-hoc networks. Typically these proposals assume that no infrastructure is available on highways, and the vehicle-to-vehicle network operates on pure ad-hoc manner. We propose a system architecture that, with base stations placed along the road and acting as cluster heads, the network is partitioned into clusters.

With this system architecture, we designed a generic TDMA scheme for the MAC layer protocol to take advantage of the fixed cluster heads in the network. In our system architecture, when a vehicle wishes to establish a connection with another vehicle, it sends the request to the base station. Based on the wireless signal interference model, the base station selects intermediate relay vehicles (nodes) for the connection from source node to destination node, and assigns channels to these nodes. This process is repeated periodically to offset the effect of high node mobility. We define and implement a greedy algorithm for relay node selection and channel assignment.

Network capacity is a very important parameter in evaluating a new network architecture.

In this thesis, we focus on the network capacity of the proposed architecture, in terms of the number of requests being accepted. Specifically, we investigate network throughput under the greedy algorithm. We identified four network parameters: transmission range, node density, number of requests and number of available channels. Also, online and offline scheduling algorithms are implemented and compared. We performed a simulation of the network's steady state, which yield the following findings:

1. In steady network state, network throughput using greedy algorithm is approximately 70% of the theoretical best case average throughput.
2. Node density has significant impact on network throughput when inter-node spacing is comparable to the transmission range. In our simulation, this happens when the transmission range is 50 meters and inter-node spacing is about 8 meters. This is due to the effect that closer relay nodes are chosen because of shorter transmission range. When transmission range is significantly greater than inter-node spacing (transmission range =100 meters, inter-node spacing is about 8 meters), node density only has marginal effect on network throughput.
3. When the transmission range is greater than 200 meters, network throughput begins to decline, due to the larger interference range of each transmission node.
3. Offline shortest-first scheduling normally outperforms online scheduling, because offline shortest-first scheduling gives priority to shorter connections, thus improving the network channel re-usability.
4. A hotspot in the network typically improves network throughput by denying long connections across the hotspot area, thus improving network locality and channel

re-usability.

Vehicles on highways have special moving patterns, sometime these special mobility causes transient states in the network. In this thesis, we simulated the effect of three different transient network states on network throughput: merging vehicle packs, stop-and-go waves, and gaps in the traffic flow. Simulation results show that the vehicle-to-vehicle network is resistant to slight stop-and-go waves in the traffic flow, and the network throughput is stable throughout this network disturbance. Although stop-and-go waves cause non-uniform node distribution in the network, only a small fraction of nodes (i.e 10 out of 244) get involved in this network disturbance, therefore the overall effect is negligible. However, network throughput is greatly affected by gaps in the network. When there is gap in the network, either the nodes on the edge of the gap are overloaded or the network is partitioned. The overall effect is that accepted connections are more localized, and network throughput is improved. We also demonstrated the effect of packs merging in the network and showed the changes in inter-pack/intra-pack connections during the merging process.

5.2 Future Research

For future research of the novel system architecture proposed in this thesis, we suggest the following directions:

1. More accurate theoretical estimation on network throughput and better algorithm for

channel assignment

In the thesis we compared the simulation result with the theoretical best case average throughput, and our simulation result is about 30% off from the theoretical. The theoretical result is for the best case scenario in that a simplification (connections in opposite directions can share the same channels) is used in its derivation process. A theoretical result that does not depend on the best case scenario would be a better benchmark to evaluate channel assignment algorithms. Also, it is interesting to find out whether there is a better channel assignment algorithm, or if there is an algorithm that gives optimum channel assignment.

2. Design of the inter-cluster protocol

In this thesis, we focused on the network capacity within one cluster. However, one connection could span two or more clusters, thus inter-cluster algorithm is needed to take care of channel assignment for these connections. Specifically, the inter-cluster protocol should solve the problem of how two clusters synchronize with each other on whether one inter-cluster connection should be accepted or rejected. The results from this thesis provide a solid foundation for comparing different inter-cluster channel assignment algorithms.

3. Vertical Handoff Algorithm

As described in the CALM model in the introduction section, networks of different technologies are going to coexist and overlay each other. One interesting problem is the algorithm on performing handoff from one network to another network to maximize performance (maximum bandwidth, lowest cost, etc.). For example, when traffic is sparse and vehicles are far away from each other, vehicle-to-vehicle multihop communication may have lower data rate because of longer transmission range; therefore handing off to a 3G network may be a good choice if bandwidth is critical. However, during rush hours on the highway, when there are plenty of vehicles for relay, using the vehicle-to-vehicle multihop network could be a better choice.

4. Algorithm for vehicle-to-base station connection channel assignment

In this thesis, we considered vehicle-to-vehicle multihop communication, assuming base station act solely as a controller. Base stations can also act as Internet gateways, and vehicle-to-base station high speed connections may be established. Base stations can use nearby vehicles to relay packets to the destination cars using vehicle-to-vehicle multihop connection, similar to the algorithms we described in the thesis. The only difference is the algorithm to choose the first hop vehicle from the base station. Base stations can apply different strategies to select a nearby car. For example, base stations can predict which car is going to stay in its range for the next scheduling interval according to the vehicle speed and location, and make selection accordingly. Also, channel fading models for Vehicle-to-Roadside Unit (V2R) and Vehicle-to-Vehicle (V2V) are also worth studying.

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