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Decentralized Traffic Information System Design
Based on Inter-Vehicle Communication

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ABSTRACT OF THE DISSERTATION

Decentralized Traffic Information System Design
Based on Inter-Vehicle Communication

by

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As traffic congestion continues to grow on our roadway systems, trip travel times are becoming less consistent and less predictable. To help travelers conduct better trip planning, traffic information systems are becoming increasingly valuable. These traffic information systems can be used both off-board (e.g., on the Internet prior to trip departure) or on-board, where several navigation systems exist that can provide real-time traffic information. Most traffic information systems are based on a centralized architecture focused around a traffic management center that collects, processes, and disseminates traffic data. As an alternative approach, there has been recent interest in *decentralized* traffic information systems, i.e., those that are based on using inter-vehicle communications (IVC).

This dissertation presents a decentralized traffic information system design based on inter-vehicle communication. As IVC-equipped vehicles travel the roadways, they can share information on network traffic conditions and regional traffic information can be soon established. Decentralized systems avoid potential single point failures that a traffic management center (TMC)-based system might have and are capable of covering

roadways that do not have embedded loop detectors. This dissertation has several key contributions:

- Several techniques have been investigated on how traffic information can be collected, processed, and shared within a decentralized IVC-based traffic information system. These techniques vary from simple blind averaging between all participating vehicles, to more sophisticated techniques using decay factors or filtered estimation.

- Adaptive dissemination mechanisms have been proposed and evaluated. Each participating vehicle can adapt their transmission parameters (transmission interval or power) according to the current traffic environment.

- An analytical model has been developed to examine the effect of the key parameters on system performance.

- An integrated traffic/communication simulation environment has been implemented to simulate the effectiveness of this decentralized traffic information system.

Based on the simulation results, it can be seen that by using the proposed adaptive dissemination scheme together with a well-design estimation algorithm, a 5% IVC-equipped vehicle penetration rate can achieve more than 90% road traffic information accuracy under typical conditions.

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Chapter 1

Introduction

Wireless communications will certainly play an important role in future vehicle and traffic operations. There are many application areas in this arena, including information services (e.g., telematic systems such as General Motor's On-Start System [1]), enhancing vehicle safety (e.g., National Highway Traffic Safety Administration's Intelligent Vehicle Initiative [2]), and providing infotainment to passengers. In the national Intelligent Transportation System (ITS) architecture, four distinct modes of communications have been defined to support this diverse collection of applications and services, including: 1) wide-area broadcast communications; 2) wide-area two-way wireless communications; 3) short-range vehicle-infrastructure communications; and 4) inter-vehicle (i.e., vehicle-to-vehicle) communications [3].

Inter-vehicle communication (IVC) has been one of the more active areas of research, primarily in the area of Automated Vehicle Control and Safety Systems (AVCSS). Much of the early work has focused on the application of an Automated Highway System (AHS), where vehicles organize themselves in platoons (i.e., groups of vehicles traveling together with short inter-vehicle spaces) [4-6]. More recently, IVC research has been directed at safety systems [2]. Comparatively less attention has been paid to IVC for

Advanced Transportation Management and Information Systems (ATMIS), since this is typically handled with vehicle-to-infrastructure, wide-area, or wireline communication systems. For example, fixed sensor networks already exist in the roadways to monitor traffic counts, average speed, and traffic flow (see, e.g. [7]).

However, existing traffic monitoring systems can be significantly enhanced with IVC. The idea of sharing information among vehicles in the traffic stream is not new and has been suggested in many concept papers. It is essentially an extension of the transportation management concept of collecting localized roadway information (such as average speeds and link travel times) from "probe vehicles" that are operating in the traffic stream. Probe vehicle information is typically transmitted to a centralized server (e.g., a transportation management center), combined with fixed sensor information, and processed. The traffic information system then disseminates current traffic conditions to travelers to help drivers adjust their routes and avoid congestion, thereby increasing the efficiency of the existing roadway system.

Rather than depending entirely on a centralized traffic information system which has limited coverage and can suffer from potential single-point failures, several researchers have begun to investigate decentralized traffic information systems [8-11]. These decentralized traffic systems are based on IVC and are fully decentralized. Traffic information such as position, average speed, and link travel time are sensed by each individual vehicle. The information is processed and combined with information received from other vehicles and distributed in the form of broadcast packets. Due to the highly distributed nature of inter-vehicle ad hoc networks, this type of system can disseminate

local detailed traffic conditions in a very short amount of time. Thus the decentralized traffic information system can be complementary to conventional traffic information systems.

There are several key challenges in a decentralized network approach. First, one of the most critical issues is how to control transmission channels without any base stations on the roads. The environment is highly dynamic and the density of vehicles can vary from only a few vehicles per kilometer-lane to upwards of 300 vehicles per kilometer-lane in traffic jam situations. Additionally, depending on the transmission range of the wireless interface, these vehicle densities can change completely within the order of seconds – for example if a vehicle on a road with very low traffic density intersects with a crowded highway. In decentralized traffic information systems, the data collection, processing, and dissemination lies entirely with each individual vehicle. Therefore a good inter-vehicle communication dissemination scheme should take these vehicular environment situations into consideration and it is crucial so that information is readily available for traffic estimation and the precious wireless bandwidth is conserved. Secondly, there is no centralized processing center. Each individual vehicle needs to estimate traffic conditions individually based on the traffic information sensed by itself and that received from its neighbors. Thus the design of traffic estimation algorithm is quite different from that used in the centralized approach and needs to be evaluated. To date, these two aspects of the system design have only been studied separately. The design of the dissemination mechanism highly depends on the traffic data requirements of the application and on the related traffic estimation algorithm that is used.

There have been several studies in recent years that address decentralized traffic information systems. In [9], the authors have modeled information propagation and have studied the effectiveness of such a zero public infrastructure vehicle-based traffic information system. However the emphasis of this paper is focused on the traffic flow point of view and really doesn't consider the details of communication. In [8] a decentralized traffic information system design is presented based on periodic reports of traffic conditions in each vehicle's knowledge base. However its periodic reports will likely suffer from packet collisions under high traffic density conditions or from missed communication opportunities during high (relative) velocity situations. Wischhof et al. presented a "provoked" broadcast scheme for travel and traffic information distribution based on IVC in [10-11]. The provoked broadcast scheme can adapt the inter-transmission interval based on the local environment and based on knowledge gained from the received packets. However a disadvantage of this proposed scheme is that when a strong provocation occurs, all nodes will reduce their transmission interval, which can cause an increase of packet collisions. In [12], the authors presented a smart dissemination scheme for a zero-infrastructure traffic information system based on using a cellular network, which has limited bandwidth compared to a short-range wireless link (e.g., 802.11) and in which every transmission has a cost associated with it. In [13], Xu et al. proposed 2-layer protocols for a vehicle to send safety messages to other vehicles. The protocols are based on the idea of repetitive transmissions, which is not really suitable for traffic information applications. Furthermore, these papers to date have focused primarily on either the traffic flow or communication point of view. None of these studies have

considered the design of the travel time estimation algorithm and its effect on system performance in such a decentralized system.

Given the limitation of existing studies on the design of decentralized traffic information system, in this dissertation, we first evaluated different algorithms that estimate travel times in a decentralized IVC-based traffic information system. These algorithms vary from simple blind averaging techniques among all participating vehicles to more sophisticated techniques using decay factors. Through the extensive simulation experiments, we show that the type of algorithm can have a dramatic effect on overall system performance, primarily in the accuracy of true travel times. A blind averaging technique can cause serious problems due to the fact that the value of early estimates may dominate the final result. Improvements can be made by introducing a decay factor in the averaging estimates, but the result is still beyond the acceptable range. Significant improvements can be made by only allowing single values of all vehicles that have directly experienced link travel times. In this case, 97% of the links in the network have estimated link travel time errors less than 10%. This level of error is acceptable for an effective traffic information system.

Second, we proposed an adaptive interval control broadcast scheme for an IVC-based decentralized traffic information system in this dissertation. In the proposed design, each participating vehicle can adapt their transmission interval according to the current traffic speed and also disseminate the traffic information of different roadway segments at different rates according to the distance from its current position. Since the 802.11a standard has been selected by the ITS Dedicated Short Range Communication (DSRC)

standard committee as the MAC layer protocol, we also investigated the use of 802.11a wireless link in our system.

This dissertation is organized as follows. Chapter 2 reviews related work and provides related background and literature review, including Intelligent Transportation Systems, Advanced Traffic Information Systems, Inter-Vehicle Communications and basic traffic characteristics and measurements. Chapter 3 describes the overall system architecture of the decentralized traffic information systems. A unique simulation model, which has been developed to analyze the efficacy of decentralized IVC-based traffic information system, is introduced in Chapter 4. Chapter 5 evaluates different algorithms that estimate travel times in a decentralized IVC-based traffic information system. We propose an adaptive interval control broadcast scheme for an IVC-based decentralized traffic information system in Chapter 6. The simulation results of the overall system performance are also given and discussed in Chapter 6. An analytical model has been developed to examine the effect of the key parameters on the system performance in Chapter 7, followed by conclusions and future work.

Chapter 2

Background and Literature Review

2.1 Intelligent Transportation Systems (ITS)

For many years, traffic congestion has been a huge and constant problem in urban areas around the world. As vehicle travel continues to outpace growth in roadway capacity, congestion continues to get worse. In previous decades, additional roadways were built to meet the increasing transportation demands. But now, because of the lack of suitable land to build on and environmental impact issues, it has been realized that increases in transportation system services must come from efficiency improvements rather than new roadways. Within the vehicular transportation community, new applications and services called Intelligent Transportation Systems (ITS) have generated considerable attention over the past decade. Researchers are developing high technology ITS solutions to improve the performance of traffic systems. A critical part of ITS is a broad range of wireless and wireline communications-based information, control, electronic technologies. When integrated into the transportation system infrastructure, and in vehicles themselves, these technologies help monitor and manage traffic flow, reduce congestion, provide improvements to roadway safety, enhance mobility of people

and goods, reduce energy consumption and vehicle emissions, and increase the capacity of the existing highway infrastructure in congested urban areas.

The National Intelligent Transportation Systems (NITS) Architecture [3] has identified 32 different services that are bundled into eight user service areas: 1) travel and transportation management; 2) public transportation management; 3) electronic payment; 4) commercial vehicle operations; 5) emergency management; 6) advanced vehicle control and safety systems; 7) information management; and 8) maintenance and construction management.

Communications networks are among the fundamental structural elements that make up an intelligent transportation infrastructure, because they serve as the paths ITS services use to access and share information. These networks link disparate ITS applications to each other and to centralized management centers, allowing for the key functions of data gathering, synthesis, delivery, and broadcast to occur in real time. Because of their importance to ITS, the NITS architecture defines five distinct modes of communication to support its diverse collection of applications and services:

1) Wide Area Broadcast Communications, such as that provided to an automobile's FM radio receiver;

2) Wide Area Two-Way Wireless Communications, which allows more advanced, interactive services over, for example, a cellular phone link;

3) Dedicated Short Range Communications, such as wireless vehicle "tags" for toll collection;

4) Vehicle-to-Vehicle Communications, which will someday endow vehicles with collision-warning and avoidance capabilities and will play a critical role in automated highway systems; and

5) Wireline Communications, which include regular "phone line" devices and high-speed data networks.

Moreover, individual applications may utilize several communications modes, and impose different performance requirements on the network in terms of bandwidth, latency, and quality of service (QoS). As a result, specific wireless communication architectures and methods are being developed for particular ITS applications within the vehicular transportation community (e.g., see [24-27]).

Figure 2.1 shows the 21 subsystems that comprise the national ITS physical architecture. The 21 subsystems can be grouped into up to four basic classes: the centers; the roadside; the vehicles; and the travelers. The subsystems represent aggregations of function that serve the same transportation need. For example, the traffic management subsystem (one of the 10 center' subsystems) represents the functions typically performed by a traffic control center. The roadway subsystem (one of the four roadside subsystems) is comprised of roadside devices such as traffic controller, traffic signals, loop detectors, and cameras. The vehicle subsystem corresponds to the five different types of vehicles using the transportation system – passenger cars, transit vehicles, commercial vehicles (trucks), and emergency vehicles and maintenace and construction vehicles. The travelers subsystem represents the different ways a traveler can access information on the status of the transportation system. Figure 2.1 also shows the different

communication classifications connecting the different subsystems. As can be seen, wireline communications can be used to connect the center's subsystem to the roadside subsystem; an example includes fiber-optics networks used to connect traffic control centers to freeway loops and variable message signs (VMS). Wide-area wireless communications can be used to connect remote travelers to the different components of transportation system. DSRC involves communications between vehicles and roadside reader. Finally, vehicle-to-vehicle communications refer to communications between the vehicles.

Figure 2.1 National ITS Architecture subsystems and communications (From [30])

2.2   Advanced Traffic Information Systems

Advanced Traffic Information System (ATIS) is an area of ITS applications. Recent advances in electronics and micro-computing have led to the feasibility of functionally powerful, computer-based advanced traffic information systems as part of the automotive environment. Although these systems range in functionality, they all have the goal of acquiring, analyzing, communicating, and presenting information to assist travelers in moving from a starting location to a desired destination. The systems improve travel safety, efficiency, and comfort and represent a new frontier in ground transportation.

2.2.1 Centralized Traffic Information Systems

The conventional traffic information systems typically involve a central authority that collects data from the street network, processes them in traffic management centers and disseminates traffic analysis result to the drivers [28]. The architecture for a typical centralized traffic information system is shown in Figure 2.2. The system typically consists of a control center, sensors deployed along the roadside, and radio broadcast stations. Traffic data including vehicle speed and traffic flow are collected via embedded sensors in the street network and sent to a central Traffic Management Center (TMC) for processing. The current traffic situation is analyzed in the TMC and the result of this situation analysis is forwarded to the radio broadcast station, transmitted to variable message sign, or placed on the internet to warn of congestion and give travelers information about special events. Travelers use received traffic situation information to adjust their driving route. This type of systems is becoming common in urban areas

around the U.S. For example, California Traffic Performance Measurement System (PeMS) [7] is a freeway traffic performance analysis system using the data collected by the loop detectors instrumented in all major urban freeways in California. The disadvantage of this centralized approach is it requires substantial initial investment on roadside communication facilities, sensing devices and data computing centers. The traffic information service is limited to roadway where sensors are integrated into the pavement.

Figure 2.2 Typical centralized traffic information system

Another solution is to instrument a fraction of the vehicles, which are often called "probe vehicles", on the road to complement fixed sensors to collect information about the current conditions. Wireless communications, such as Cellular Digital Packet Data (CDPD) and General Packet Radio Service (GPRS), can be used to transmit probe vehicles' current locations and speeds to traffic information centers. Many researchers

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have proposed using Automatic Vehicle Location (AVL)-equipped transit vehicles as probe vehicles for estimating traffic information [31-33]. Most existing AVL systems are used primarily for managing transit operation in real time and the transit can respond to changes in traffic flow as they traverse the network. Probe vehicle programs can be divided into two basic types: systems based on fixed receivers that sense transponders in vehicles as they drive by, and free-roaming vehicles that transmit data to a central station at periodic intervals. The first type utilizes the signpost system in which a series of radio beacons are placed along the bus routes. The identification signal transmitted by the signpost is received by a short range communication device on the bus. Since the location of each signpost is known, the location of the bus at the time of passing the signpost is determined. This type of system is inexpensive for the individual vehicles, but it requires significant infrastructure for the fixed transmitter. An example of the second type of system (floating car) often utilizes Global Positioning System (GPS) receivers to determine position and velocity. Being less expensive and more accurate, GPS is becoming dominant technology deployed for locating the vehicle for AVL. GPS-equipped vehicle can transmit location and travel time data to a traffic management center at frequent intervals [34]. This type of system requires significantly more components in each vehicle, but has the advantage of little or no roadside infrastructure. The work by Chen et al [37], Ferman et al [35], and Dai et al [36] evaluated the floating probe vehicle technique and demonstrated that it is feasible to use floating vehicle as traffic information sensors.

The probe-based traffic information system doesn't need the deployment of a large number of sensors and the traffic information service can be extended to the local streets that probe vehicles can traverse. Similar to the first type of traffic information system, the collected data from probe vehicle are sent to traffic management center and evaluated. Since a central unit covers a relatively large area and due to the limited bandwidth for transmitting the traffic messages, the broadcasted information needs to be general and cannot include specific details on the area close to the current position of the driver.

2.2.2 Decentralized Traffic Information Systems

The concept of a zero public infrastructure vehicle based traffic information system is introduced in [9]. This paper mainly focused on traffic flow issue. The authors modeled the information propagation and studied the probability distribution of time lag. In contrast to the centralized approach, a self-organizing traffic information system (shown in Figure 2.3), which is based on inter-vehicle communication, is fully decentralized. Because of the GPS receiver mounted in the vehicle, the participating vehicles will be able to determine their current location and past spatial-temporal trajectory information as they traverse the network. Data such as percentage stopped time, speed of a vehicle circulating in a network, and travel time to traverse a road segment could be used to assess the congestion level. Vehicles exchange these traffic measurements as they are moving through the network, which allows drivers to calculate the optimal route to a given destination and avoid congestion or incidents. This kind of system can disseminate local detail traffic conditions with very short latency and thus can be complementary to

the conventional centralized traffic information systems. A self-organizing traffic information system has many advantages: no initial investment for roadway infrastructure, no system maintenance, and detailed information for the local area with low delay.

Participating vehicle

Figure 2.3 Decentralized traffic information system based on inter-vehicle communication

An example of system operation is shown as Figure 2.4 (from [9]). Supposed that when each vehicle passes a link, it can always receive information from vehicles moving in the opposite stream, which are omitted in the graph, and thus knows the traffic information of the opposite stream. Vehicle A departs node 3 to node 10 and meets Vehicle B, which departs node 10 to node 11, on link (9, 10) at time t_1. Vehicle B obtains the information on link (3, 6), (6, 3), (6, 9) and (9, 6). When Vehicle B meets Vehicle C on link (7, 4) at time t_2, it obtains the updated information on link (3, 6). After comparing the time-stamp, Vehicle B will replace the old information with the new one. The destination of Vehicle D is node 6. When it meets Vehicle B at time t_3, it knows the

information on link (1, 4), (4, 5), (5, 6), (3,6) from Vehicle B and use it make a decision on its route selection.

Figure 2.4 Example of vehicles exchanging information on a network

Communication implementation for such a zero public infrastructure and self-organizing traffic information system has been presented in several papers [8] [10] [11] [37] [38]. In [37], a simple multi-hop broadcast technique for the distribution of traffic information generated by a vehicle is proposed. Packets received from surrounding vehicles are forwarded in order to extend the information range beyond the transmission range of a single vehicle. In [38] a layered data structure is used, which allows a forwarding node to reduce the packet size by discarding non-relevant information. The idea is to exploit the fact that the needed accuracy of traffic information is distance-dependent. Both [37] and [38] use a broadcast based flooding approach to distribute

emergency or traffic jam information within an area very close to the vehicle and is limited to a few hops. In [8] each vehicle transmits an update of its current position and traffic information periodically. Traffic information can be propagated farther compared to the implementation in [37][38]. However its periodic report will result in packet collisions in high traffic density or the risk of missing communication opportunities in a high relative velocity situation. Wischhof et al. presented a "provoked" broadcast scheme for travel and traffic information distribution based on IVC in [10-11]. The provoked broadcast scheme can adapt the inter-transmission interval based on the local environment and based on knowledge gained from the received packets. Furthermore, the research on self-organizing traffic information system to date has focused primarily on either the traffic flow or communication point of view. None of these studies have considered the design of the traffic estimation algorithm and its effect on the design of information dissemination mechanism as well as system performance in such a decentralized system.

2.3 Inter-Vehicle Ad Hoc Networks

In the ITS research community, inter-vehicle communication has attracted the interests of many automobile manufactures and researchers with the decreasing cost of components for communication and positioning in the recent past. Various research projects were initiated [40-42], some explicitly focused on inter-vehicle communications, others considering inter-vehicle communications as one of many possibilities for data distribution. Increasing interest in roadside-to-vehicle communications and inter-vehicle

communication also led to various standardization efforts worldwide, e.g., for a suitable wireless interface [39].

Much of the early work on inter-vehicle communication has focused on the application of an Automated Highway Systems (AHS) in the area of Automated Vehicle Control and Safety Systems (AVCSS) [4-6]. In this scenario, automated agents take over complete control of all steering, acceleration and braking functions for multiple vehicles traveling together at high speed in a tightly-packed formation called a platoon. By forming organized platoons, it is possible to increase traffic flow well beyond what is achieved with manual driving. In much of the early work, every vehicle in a platoon informs each other it's current operational parameters, including both telemetry data (i.e., its current speed, the level of power of braking being applied, steering angle, etc.) and any planned actions it may wish to initiate (i.e., lane change or exiting freeway), through line- of-sight communications by millimeter wave or infrared in narrow area.

In contrast, a type of more progressive inter-vehicle communication operating in wide areas, which is most efficiently served by ad hoc networks, has become a major topic during the last few years. A wireless ad hoc network is a collection of autonomous nodes or terminals that communicate with each other by maintaining connectivity in a decentralized manner. Each node in a wireless ad hoc network functions as both a host and a router, and the control of the network is distributed among the nodes. The network topology is in general dynamic, because the connectivity among the nodes may vary with time due to node departures, new node arrivals, and the possibility of having mobile nodes. Since the nodes communicate over wireless links, they have to contend with the

effects of radio communication, such as noise, fading, and interference. In addition, the links typically have less bandwidth than in a wired network. The vehicles form a dynamic, ad hoc network. In such a inter-vehicle communication scheme, no infrastructure is required for communications between vehicles. Each vehicle is a node capable of sending/receiving/replaying messages to/from/to neighboring vehicles via wireless media. Information is distributed, acquired, or exchanged on top of this network.

Although inter-vehicle ad hoc networks fall in the class of mobile ad hoc networks, it behaves in fundamentally different ways than the models used in mobile ad hoc networks research. In mobile ad hoc networks, the nodes are generally assumed to follow the random waypoint mobility mode [12]. In this model each node randomly selects a waypoint in the area that contains the network and moves from its current location to the waypoint with a random but constant speed. Once a node has arrived at the waypoint it pauses for a random amount of time before selecting a new waypoint. This movement pattern of nodes has no similarity to the behavior of vehicles, the random waypoint model seems to be inappropriate to investigate the characteristics of vehicular ad hoc networks. The movement models in a vehicular ad hoc network differ from typical mobile ad hoc networks models in several ways. First, vehicles move with acceleration/deceleration, lane-changing and car-following behaviors. Second, the vehicles in vehicular ad hoc networks are generally assumed to move much faster than the nodes in mobile ad hoc networks. Vehicles can move at a high speed such as 120Km/hr. In the past studies, however, mobile nodes are generally assumed to move at a much lower speed. Third, vehicle in vehicular ad hoc networks can only move along the roadway while the nodes

in mobile ad hoc networks are assumed to move freely in any direction. Although many studies about mobile ad hoc networks have been done in the past, their results may not be applicable to an inter-vehicle communication network due to these differences. The results obtained from past studies about mobile ad hoc networks require re-inspection for their suitability for inter-vehicle communication networks. In [43] and [44], the authors studied and evaluated the performance characteristics and the effectiveness of distributing information among vehicles using inter-vehicle communications. These characteristics have important implications for the design decisions in these networks. The authors proposed a GPS-based message broadcasting method for inter-vehicle communications in [45]. A GPS-based unicast routing scheme for cars by using a scalable location service is proposed in [46]. In [47], the authors showed that messages can be delivered more successfully, provided that messages can be stored temporarily at moving vehicles while waiting for opportunities to be forwarded further. In [48], the authors studied how effective a vehicle accident notification message can be distributed to vehicles inside a relevant zone.

In general, two different approaches can be distinguished: flooding the local area (limited by the number of hops or geocast) of the vehicle or using an ad hoc routing mechanism to establish a connection from one vehicle to a vehicle further ahead. An example for the flooding technique is [37], where hop-limited flooding is used for the dissemination of traffic information. Additionally, a layered data structure allows a forwarding node to reduce the size of a data packet by discarding information. The idea is to exploit the fact that the required accuracy of traffic information is distance dependent.

The system proposed in [49] also uses hop-limited flooding, but maintains a set neighboring nodes and known sender of the message. If no neighbor for forwarding the message is in range, the message is stored until the set of neighbors change.

Ad hoc routing-based approaches are proposed, e.g., in [46, 50, 51]. In [50], modifications of ad hoc on-demand distance vector (AODV) routing for vehicular environments are discussed. Reference [51] presents a beaconless routing protocol for highly dynamic network topologies. Carnet [46] is a location service for geographic routing in vehicular networks. However the information range achieved with routing-based approaches is limited by the multihop range and, thus, rather short in cases of a low density of equipped vehicles.

Compared to the previously mentioned approaches, the method proposed in this paper is different in various aspects: the transmission and reception of data packets is completely decoupled, no routing is required, and the rate at which a node sends data packets is adapted to the local environment.

2.4   Basic Traffic Characteristics

In order to better understand the algorithm in this dissertation, a short description on traffic flow fundamentals is in order. The fundamental characteristics of traffic are flow, speed, and density [52]. Density is also related to the gap or headway between two vehicles in the traffic stream. A brief definition of these elements follows:

- Flow rate is defined as the number of vehicles passing a point in a given period of time usually expressed as an hourly flow rate per lane. An important flow

parameter is the maximum flow rate, which is often referred to as the capacity of a roadway.

- Speed is the distance traveled by a vehicle during a unit of time. Speed is usually expressed in miles per hour or kilometer per hour. There are two important speed parameters: the free-flow speed and the optimum speed. The free-flow speed is the absolute maximum speed that is attained when the flow approaches zero. The optimum speed, on the other hand, is the speed of the traffic stream under maximum flow conditions (i.e., capacity conditions).

- Traffic density is defined as the number of vehicles occupying a length of roadway at a given instant in time. Density is typically expressed in vehicles per mile or vehicle per kilometer. There are two important density parameters: the jam density and the optimum density. The jam density occurs under extreme congestion conditions when the flow and speed of the traffic stream approach zero. The optimum density occurs under maximum flow conditions.

- Headway is the time or distance gap between two successive vehicles in the traffic stream. The time headway is defined as the difference in time between the moment a vehicle arrives at a point on the highway and the moment the following vehicle arrives at that same point. The time headway is typically expressed in seconds. The space headway, on the other hand, is defined as the distance between the front of a vehicle and the front of the following vehicle.

The traffic handling on a road section can be represented in a space-time diagram (Figure 2.5). Vehicle A traverses the whole road segment ab using time $t'-t_1$. The

distance headway between vehicle A and B is *sb*, while $t''-t'$ is the time headway between vehicle A and B.

Figure 2.5 Example space-time diagram of a road section

A linear equation can be used to approximate the relationship between the speed and density of traffic flow on an uninterrupted traffic lane, as shown in Figure 2.6 (a). Based on this, the relationship between the speed and flow, and that between the flow and density can be derived, as shown in Figure 2.6(b) and Figure 2.6(c).

Based on those relationships, we can find the analytical equations among the speed, flow and density as:

$$v = A - Bk \tag{2.1}$$

$$q = kv = Ak - Bk^2 = -B(k - \frac{A}{2b})^2 + \frac{A^2}{4B} \qquad (2.2)$$

where v is the mean speed of vehicles (mph), q the average flow of one hour (veh/hr),

k the average density of vehicles (veh/mi), and A, B are two empirically determined

parameters. From Figure 2.6, we find the jam density is equal to $\frac{A}{2B}$, the optimum speed

is $\frac{A}{2}$, and the maximum flow is $\frac{A^2}{4B}$. The solid lines in Figure 2.6 are called "free"

traffic flow conditions while the dashed called "congested" traffic flow conditions.

(a) Density vs Mean Speed
(b) Volume vs Mean Speed
(c) Density vs Volume

Figure 2.6 Relationships among speed, flow and density (from [52])

The concept of Level of Service (LOS) can be used as a means of describing the quality of traffic operations within a traffic stream and at a given location. Six LOS are defined using letter designations for each level, from A to F, with LOS A representing the best operating condition and LOS F the worst. This quality is generally described in terms of speed and travel time, ratio of flow and capacity, delay time, freedom to maneuver, traffic interruptions, as well as comfort and convenience. Table 2.1 is an example for a highway situation [52]. It shows the relationships among traffic speed, flow and density for a highway, and how these factors relate to LOS ratings.

Table 2.1 Level of Service for Basic Freeway Sections [52]

LOS	Speed Range (mph)	Flow Range (veh/hour/lane)	Density Range (veh/mile)
A	Over 60	Under 700	Under 12
B	57-60	700-1100	12-20
C	54-57	1100-1550	20-30
D	46-54	1550-1850	30-42
E	30-46	1850-2000	42-67
F	Under 30	Unstable	Above 67

Because of the relationships between LOS and speed, flow and density, the quality of traffic operation can be measured by the traffic data collected from the streets.

Chapter 3
System Architecture

According to the description in the previous chapter, a decentralized traffic information system can be regarded as a novel autonomous location-aware information system where objects (vehicles) equipped with sophisticated sensors, collect information about their physical environment. They either report this information in response to queries or periodically disseminate it to surrounding objects. Examples of such data that can be collected include traffic conditions (e.g. travel times) as measured by the instrumented vehicles that make up the decentralized traffic information system. Travel times, measured by one instrumented vehicle, are of interest to other cars that are likely to take that route. In such a system, each vehicle serves as a mobile sensor that contributes a small piece of information to the overall "picture", which is aggregated from multiple such individual reports. The system can consist of a massive number of individual agents (participating vehicles in a decentralized traffic information system) that move around, collect, summarize, and classify information about their immediate physical environment. It is different from the typical sensor environment since it relies on mobile sensors rather than on a fixed predefined infrastructure. Each individual agent can visit areas that are not instrumented by stationary sensors. Also, agents can offer multiple

reports of the same physical space, i.e., vehicles traveling through the same road segment. This highlights two important characteristics of such a system: redundancy, which imparts robustness, and dynamic nature of coverage, which changes with the location of its agent. This architecture has the potential to create a highly scalable and robust information acquisition system.

3.1 System Overview

Our goal is to design a system that exploits existing infrastructure and requires minimal or zero additional infrastructure. Systems based on such designs will have low deployment and maintenance costs. We believe such systems have the best chance of being deployed on a large scale. In such a system every participating vehicle would be equipped with an on-board integrated device. This device is responsible for sensing, collecting, analyzing and disseminating traffic information (this is described in more detail in the next subsection). The device can also connect to the in-vehicle navigation system, supplying current traffic conditions for the driver. From a user's (driver) perspective, this device appears as a black box. A user only interacts with the in-vehicle navigation system posing navigational queries. The in-vehicle navigation system, in turn, queries the on-board integrated device to obtain current traffic information on various road segments, computes an optimal route, and displays it to the user. Figure 3.1 shows the schematic diagram for the system, which is described in the next section. The important features of this system are:

1) The system consists of a large number of highly mobile sensor. This has two consequences:

   - The coverage provided by the vehicles is dynamic and changes with the location of vehicles.

   - Multiple vehicles may sense the travel time of each road segment at approximately the same time, introducing redundancy in information collected by the vehicles. This redundancy is critical to the reliability of the system.

2) Turning vehicles into traffic sensors has the advantage that zero additional infrastructure is required. However the disadvantage is that awareness of traffic information on a road segment is available only if there is relatively uniform flow of vehicles through that segment. If there is no temporary "witness", that information is not available. But when a significant fraction of vehicles are instrumented, then if there are no witnesses to traffic on a given road segment it means that there is no traffic.

3) Density of participating vehicles in an area may vary dramatically with time (e.g. it may drop substantially at night) and space (e.g. rural regions typically have lower vehicle density than urban regions). The fact that traffic information is needed well in advance coupled with the fact that density of vehicles may vary dramatically with space and time, have direct implications on design of the specific dissemination mechanism via inter-vehicle communications. This is discussed in more detail in Chapter 5.

4) There is no centralized processing center in such systems. Each individual vehicle needs to estimate traffic conditions individually based on the traffic information sensed by itself and that received from its neighbors. Therefore the design of the traffic estimation algorithm is quite different from that used in the centralized approach. This has advantages in both robustness (e.g. a centralized system can suffer from a single-link failure) and in timeliness.

Figure 3.1 Block diagram of on-board integrated device presented in each participating vehicle in a self-organizing traffic information system

3.2 On-Board Integrated Device

In any decentralized traffic information system, the functionality that is implemented by a traffic management center in a conventional traffic information system is now instead handled by each individual vehicle. Therefore each vehicle should: 1) have the capability of sensing its own state (e.g., position, velocity, and link travel times); 2) be

able to make estimates of traffic conditions; and 3) be capable of inter-vehicle communication. Figure 3.1 illustrates a block diagram of the overall on-board integrated device. It is assumed that all participating vehicles have the same internal structure and the on-board integrated device of each participating vehicle consists of the following five components:

1) Global Positioning System (GPS) Receiver

The Global Positioning System is one of the most convenient and accurate methods for determining a vehicle position in a global coordinate system [22]. The system is built around a set of 24 satellites that orbit the earth. The orbits are designed in a manner that allows the signals from at least four satellites to be received simultaneously at any point on the surface of the earth. A GPS receiver on the surface of the earth can use the signals from at least four satellites to determine its own antenna position according to various measurements of the pseudoranges between the satellites and the receiver antenna. Most of current existing vehicle navigation systems utilize GPS receivers as their spatial positioning sensors. The GPS can provide very accurate timing, position and velocity information for navigation.

2) Digital Network Map

It is assumed that the digital road network map is organized by road segments, where a road segment is defined as a stretch of a road between two successive exit/entry points (junction, exits, etc) or intersections. Most digital road networks available today are already organized into road segments. For each road segment, the database stores three attributes:

- GPS coordinates of its endpoints,

- Length of the segment, and

- Free flow traveling time (Length of the segment divided by the free-flow speed limit).

Once the vehicle spatial position has been determined, the map can provide location-related features. For example, the on-board integrated device uses dynamic position and time information from the GPS unit along with the static position information of the digital roadmap's node/link database to calculate the travel time that it experiences for different road segments. When a vehicle exits a link, the corresponding travel time that it experience will be recorded with a time stamp.

3) Traffic Information Database

The on-board system also includes a simple database to store all currently available traffic information. This is simply a two-dimensional spatio-temporal database that has every road segment (link) with known traffic conditions as one axis, and time intervals as the other axis. For our initial analysis, we have chosen the time interval of interest to be 10 minutes. Traffic information is estimated based on this specific time interval. Thus for every hour, six different time periods exist and the information that is older than one hour is simply discarded. Assuming that the information in each cell in the spatio-temporal traffic information database can be represented by a single byte, the size of the database will simply be 144 bytes times the number of links (N) in the network. Even with a large network with thousands of links, the total size of the database is very manageable. Even when operating in a very large metropolitan area, network culling techniques can be used

to simply only broadcast links within a specified radius of the current location (e.g., 30 kilometers). With the advanced wireless communication technology, such as 802.11a, the information in such a database can be transmitted within a fraction of a second.

Figure 3.2 Spatio-temporal traffic information database

4) Computing and Control Unit

As we described previously, in a decentralized system, the probe vehicles communicate among themselves, therefore the traffic information needs to be combined, processed, and analyzed locally by the vehicles themselves. In each vehicle, the traffic information is estimated by an on-board computing unit. A simple example, used in the current simulations, is the following: When a vehicle exits a road segment, it averages the travel time that it experience with the travel times of all previous vehicles, based on the estimate travel time information received from vehicles in transmission range. The result is the estimated road condition for that road segment at the current time. For all other

road segments, the most recent average value received from the surrounding vehicles is used.

5) Inter-Vehicle Communication Wireless Interface

In the proposed system, a standard IEEE 802.11a wireless transceiver is used to provide vehicle-to-vehicle wireless interface. Travel time information for different road segments is disseminated among all participating vehicles using a single-hop broadcast scheme. Every vehicle can then broadcast its link travel time database to surrounding vehicles at a specific transmission interval through the inter-vehicle communication wireless interface.

3.3 Discussion

In the proposed system, link travel time estimates are a key input for dynamic route guidance systems that generate shortest-duration or shortest-distance paths between a given origin (or current position) and a given destination. A vehicle can use dynamic position and time information from the GPS unit along with the static position information of the digital roadmap's node/link database to calculate the travel time that it experiences for different road segments. When a vehicle exits a link, the corresponding travel time will be recorded. Every vehicle can then broadcast its link travel time database to surrounding vehicles at a specific transmission interval. In Chapter 6, it will be shown how the vehicle adapts the transmission interval according to the traffic environment. When a vehicle receives a packet from another vehicle, it combines the data with its own existing database. Using this method, overall traffic information can spread

rapidly among vehicles. The estimated travel time information can then be used by an in-vehicle dynamic route guidance system, which can compute a shortest duration route in real time to help the driver avoid any congestion and/or incidents.

The requirement that every vehicle be equipped with on-board integrated device may seem like a deviation from our goal of zero infrastructure design. There are two important reasons for this requirement: First, we expect vehicles in the future to come equipped with GPS devices and in-vehicle navigation systems. These two components have already started to appear in many vehicles. Also we expect other components in the on-board integrated device to be inexpensive. Second, equipping each vehicle with a device naturally makes the owner responsible for it. Thus, the cost of maintaining the system would be very small compared to that for equipment needed in existing centralized solutions.

Chapter 4

Integrated Simulation Environment

In Chapter 2, we reviewed the differences between vehicular ad hoc networks and mobile ad hoc networks. Mobile nodes in past studies are generally assumed to move freely in a random fashion at much lower speeds. In contrast, vehicles generally move on paved roads with different acceleration/deceleration events, lane-changing, and car-following behaviors. In order to evaluate the effectiveness of wireless communication to improve the efficiency of existing roadway operation, it is crucial to have a rich set of simulation modeling tools. What is needed is a fully integrated simulation environment for both traffic and communication networking simulation. Recently, vehicular traffic models have been used in many research programs to study routing strategies and communication performance characteristics in inter-vehicle ad hoc networks [53][54]. In these studies, networking function was emphasized and simple vehicle traffic models were extended to network simulators to obtain vehicle movement for network simulation. In contrast, vehicular traffic simulators can model the real word traffic system including the road, drivers and vehicles in fine detail. Therefore, for a high fidelity simulation environment, it was necessary to integrate communication networking modules into

PARAMICS, a high fidelity microscopic traffic simulator, through the use of Application Programming Interfaces (API).

The traffic simulator PARAMICS [21] consists of a suite of high performance software tools for microscopic traffic analysis. Individual vehicles are modeled on a second-by-second basis for the duration of their entire trip, providing accurate traffic flow, transit time, and congestion information, as well as enabling the modeling of different intelligent transportation system techniques. Key features of the PARAMICS model include direct interfaces to macroscopic data formats, sophisticated microscopic car-following and lane-change algorithms, integrated routing functionality, direct interfaces to point-count traffic data, batch model operation for statistical studies, a comprehensive visualization environment, and integrated simulation of ITS elements. In order to explore vehicle-based wireless communication techniques, we augmented PARAMICS to simulate inter-vehicle communications and created an integrated traffic/communication simulation environment. The diagram of this integrated simulation environment is shown in Figure 4.1. Through its API, we extended the PARAMICS features to simulate the functionality of each component in the system structure.

Figure 4.1 Diagram of integrated simulation environment

Communications are simulated between IVC-equipped vehicles using the IEEE802.11a broadcast mode [20]. The basic access mechanism (i.e., the distributed coordination function (DCF)) is a carrier-sense multiple access with collision avoidance (CSMA/CA) mechanism. The protocol works as follows. A vehicle desiring to transmit senses the medium. If the medium is free for a specified time (i.e., the DCF Interframe Space (DIFS)), the vehicle is allowed to transmit. If the channel is busy, or becomes busy during that interval, the MAC will invoke a backoff procedure to reduce the probability of colliding with any other waiting vehicles when the medium becomes idle again. A vehicle performing the backoff process will wait until its Backoff Timer (BT) decreases to 0 before it attempts to transmit again. The BT value is chose randomly from a discrete uniform distribution with values between 0 and a specified Contention Window (CW) value. The backoff timer can only start to be decremented after an idle DIFS interval. In the broadcast mode, the ready-to-send and clear-to-send (RTS/CTS) exchange is not used. The frequency is set to 5.9GHz and the Channel Bit Rate is set to 27Mbps. The

channel model described previously has been incorporated into the simulation and the parameters for wireless interface are set using the value listed in Table 4.1.

Table 4.1 Parameter Values for Wireless Interface

Transmission		Antenna	
CSThresh	-96dBm	Height	1.5m
RXThresh	-84dBm	Transmission Gain (Gt)	5dB
Frequency	5.9GHz	Receiving Gain (Gr)	5dB
Pt (1000m)	100mW		

The integrated simulation environment works as follows. The traffic simulator simulates individual vehicles every time step in a particular transportation network. Each vehicle's state such as position, speed, its surrounding environment and driving direction are recorded in vehicle state table. The traffic information broadcast of each vehicle is simulated by extended communication module integrated in PARAMICS, using the vehicle state information recorded in vehicle state table. Message propagation table stores the traffic information packets received by each vehicle. Traffic analysis is performed based on current link average speed and density. In the Knowledge base, each vehicle integrates the received information with its existing data. In Routing, vehicles adjust their route by traffic information stored in the knowledge base.

This integrate traffic/communication modeling system has prove to be quite useful for understanding a variety of IVC application as well as other ITS communication applications.

Chapter 5

Travel Time Estimation Techniques

5.1 Introduction

With steadily increasing congestion on our roadways, travel times are becoming less predictable. Traveling from point A to point B in a roadway network may vary widely depending on the time of day and which route is chosen. In order to better inform travelers of approximate travel times, there has been a significant amount of research in recent years to develop both on- and off-board navigation algorithms that can predict how long a particular trip will take. These navigation systems can dynamically select which routes to take (and update while en route) and can provide a general estimate of total travel time. These systems rely on real-time traffic information systems.

In the previous chapters, we compared the centralized and decentralized solutions for traffic information systems. In a centralized system, all collected information is sent to a traffic management center for traffic analysis, while in a decentralized system, a subset of vehicles are equipped to communicate directly with others, relaying traffic information (e.g., link travel times, average speeds, etc.) without going through a centralized traffic management center. It is important to contrast the decentralized probe vehicles' function compared to the vehicle function in a standard centralized probe vehicle system. In a

standard system, raw traffic information is relayed from the vehicles to the TMC for processing, analysis, and dissemination. In a decentralized system, the probe vehicles communicate among themselves, therefore the traffic information (in this case link travel times) needs to be combined, processed, and analyzed locally by the cars themselves. Therefore, the estimation techniques are somewhat different than a standard centralized approach and are difficult to compare.

The focus of this chapter is to evaluate different algorithms that estimate travel times in a decentralized IVC-based traffic information system. These algorithms vary from simple blind averaging techniques among all participating vehicles to more sophisticated techniques using decay factors. The efficacy of decentralized IVC-based traffic information system is analyzed, upon which each estimation technique has been rigorously evaluated.

5.2   Travel Time Estimation Algorithms

Trip travel times can be affected by various factors, such as roadway geometric conditions, speed limits, general traffic flow, and incidents. In real world applications, it is quite difficult to model the relation among all these factors. Therefore, instead of using speed or flow data collected by conventional loop detectors and converting them into travel time information, we can measure the travel times of the vehicles and use them directly in the decentralized traffic information system. As described before, each equipped vehicle calculates its own state, broadcasts its travel time information, and receives information from other vehicles. In so doing, it creates a dynamic database

indicating travel times for each network link for a specific time period. The key question is how to combine the information from all vehicles to make this database valuable for calculating route travel times. Three specific travel time estimation techniques are explored: 1) blind averaging data from all participating vehicles; 2) estimating with a decay factor; and 3) estimating only by direct-experienced vehicles.

5.2.1 Blind Averaging of All Participating Vehicles

Directly averaging the spatio-temporal databases between all participating vehicles is a very simple and straightforward estimation scheme. In this scheme, the estimated average link travel time is stored in each cell of the database. When a vehicle receives a data packet containing the entire spatio-temporal database from another vehicle, if the travel time information of a link is not included in the receiving vehicle's database, then the corresponding cell will be filled with the received value; otherwise the value will be replaced with the average of both the received cell and the previous information. The pseudo-code for this type of estimation is illustrated in Figure 5.1. Although this blind averaging scheme is very simple, it suffers from a very serious problem – the value of an earlier-generated estimate will dominate the final estimated value. The reason for this is that an earlier-generated estimate is disseminated ahead of later estimates, therefore more vehicles will obtain the earlier value thus it will be used more often in the overall averaging process. This is readily apparent when examining the simulation results provided in Section 5.3.

```
Function directly_averaging()
{
    T_dbi: the estimate value of the ith road segments in the database
    T_ri: the estimate value of the ith road segments in the receiving
         packet

    if (T_dbi is null)
        T_dbi = T_ri
    else
        T_dbi = (T_dbi + T_ri)/2
    end

}
```

Figure 5.1 Pseudo-code for estimation scheme – Directly Averaging by all Participating Vehicles

5.2.2 Estimation with a Decay Factor

Because of the inherent bias in the blind averaging scheme, a new estimation technique was devised using a decay factor α to reduce the weight of early estimates when taking an overall average. In addition to the estimated average link travel times, the latest time stamp of the actual travel times that are used to calculate this estimate is also stored in its database. Figure 5.2 illustrates the pseudo-code for the estimation scheme using a decay factor.

The value of α was determined empirically through multiple simulation runs. The value of α was varied from 0.5 to 0.9 with an interval 0.05. It was found that a decay factor of 0.8 provides optimal results.

```
Function Estimating_DecayFactor()
{
    T_dbi: the estimate value of the ith road segments in the database
    t_dbi: the latest time stamp of the actual travel times that used to
         calculate R_dbi
    T_ri: the estimate value of the ith road segments in the receiving
          Packet
    t_ri: the latest time stamp of the actual travel times that used to
         calculate R_rl
    α : decay factor

    if (T_dbi is null)
        T_dbi = T_ri
        t_dbi = t_ri
    else if (t_dbi > t_ri)
        T̂_dbi = αT_ri + (1−α)T_dbi
        else if (t_dbi < t_ri)
            T̂_dbi = (1−α)T_ri + αT_dbi
        end
    end
    end
}
```

Figure 5.2 Pseudo-code for estimation scheme – Estimating with decay factor

5.2.3 Estimating only by Direct-Experiencing Vehicles

In the previous two algorithms, the link travel times are estimated by every participating vehicle when it receives a packet from other vehicles. However in the following algorithm, the travel time estimate of a link is updated by a vehicle only when it exits that link and other participating vehicles only help disseminate the new estimate. In this case, the travel time of an equipped vehicle at a road segment is first measured and then an average travel time calculated. The travel time estimate over road segment i and the time interval $T(t_1, t_2)$ can be expressed as:

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$$T(i,t_1,t_2) = \frac{1}{n}\sum t_k \qquad (5.1)$$

where t_k is the time that vehicle k takes to traverse road segment i over $T(t_1,t_2)$, and

n is the number of sample vehicles that traverse road segment i over $T(t_1,t_2)$.

When a vehicle exits a link, the corresponding travel time t that it experienced will be recorded. In each cell of the database, the following information of a road segment is stored: average travel time $t(i)$, its timestamp t_s, and the number of accumulated samples n, where i is the corresponding road segment number. The vehicle will update the average travel time of the link by using the above equation. The number of sampled vehicles, n, will be incremented and the time when vehicle exits the road segment will be replaced with timestamp, t_s, in the database. In this particular implementation, the time interval T is set to be ten minutes and the travel time estimate is based on a smoothed average of sampled vehicles traversing road segment i. The general pseudo-code of the algorithm is given in Figure 5.3.

```
Function Estimating_DecayFactor()
{
    T_dbi: the estimate value of the ith road segments in the database
    t_dbi: the time stamp of R_dbi
    T_ri: the estimate value of the ith road segments in the receiving
        Packet
    t_ri: the time stamp of R_rl
    S_v: the road segments that the vehicle just exits
    e_e: The event that the vehicle exits the road segment S_v

    if (T_dbi is null or t_dbi < t_ri)
        T_dbi = T_ri
        t_dbi = t_ri
    end

    if (e_e)
        travel_time_estimate(S_v)
    end

}
```

Figure 5.3 Pseudo-code for estimation scheme – Estimating only by Direct-Experiencing Vehicles

Suppose an equipped vehicle exits road segment i with traversal time t. In this case, $t(i)$ will be the travel time estimate, t_s is the timestamp of the estimation with $t_s < t$, and n is the number of sampled vehicles of road segment i; all these parameters are used to calculate travel time estimate. The vehicle will update the estimate of average speed using the equation:

$$\hat{t}(i) = \frac{1}{n+1}[n \cdot t(i) + t] \tag{5.2}$$

Unlike the previous two algorithms where some travel times records might be counted in the average more than once (causing a potentially large bias), this current algorithm only includes information once from vehicles that directly experience travel on

those specific links. In this way, each true travel time will be counted as a sample once and each cell value in the database will contain only the true average of all vehicles that have experienced the link during the specific period. The actual accuracy will depend on the traffic flow of the link, penetration rate of the technique, and the variance of the experienced travel times for the link. Since all other vehicles are still participating in the distribution of the travel time estimates, the travel time information can be disseminated just as quickly in this scheme as in the previous algorithms.

5.3 Simulation Results

5.3.1 Simulation Setup

The topology of traffic network used in this study is Southern California's Inland Empire freeway network, which includes interstates I-10, I-15, and I-215 and state routes SR-60 and SR-91, as shown in Figure 5.4. In the example analysis, the transportation network model consists of 511 freeway links or segments that correspond directly to the regional freeway traffic network. The origin/destination and flow data used in the network were the typical morning peak period from 7AM to 8AM and were obtained from the local metropolitan area transportation model [23].

Figure 5.4 Example traffic network – Inland Empire Freeway Network

On the side of wireless communication, the standard IEEE 802.11 MAC protocol is used for medium access with the frequency set to 5.9GHz. According to the DSRC (dedicated short-range communication) standard, the channel data rate is set to 27 Mbps in the simulation. It is assumed that all vehicles broadcast traffic information with a fixed transmission power. In the DSRC standard, a wireless link is expected to have maximum "line-of-sight" range of 900 meters. Since line-of-sight communication is not common in inter-vehicle communication, we assume a typical transmission range of 500 meters in the simulation runs. An adaptive transmission interval control protocol is used. Suppose k is an approximate value that is greater than the ratio of maximum velocity to average velocity of a road segment, v_1 and v_2 are average speed of the road segment that the

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vehicle is traveling and that of the opposite segment respectively, and R is the transmission range. Geometrically, when two vehicles are driving from opposite directions, $\dfrac{2R}{k \cdot (v_1 + v_2)}$ is the period the transmission ranges of two vehicles start to overlap and then depart again. Therefore a transmission interval that is not greater than $\dfrac{2R}{k \cdot (v_1 + v_2)}$ is sufficient to recognize and inform any vehicle. Thus in the simulation, each vehicle adaptively adjusts its transmission interval to be $\dfrac{2R}{k \cdot (v_1 + v_2)}$. The average velocity is a space-mean average of a segment, can be obtained by $v(i) = \dfrac{t(i)}{l(i)}$, where $t(i)$ is the travel time estimate of the segment stored in the database and $l(i)$ is the length of the segment. The traffic information of the nearby links that are within radius r to the vehicle's current position is transmitted periodically at a shorter interval. The design of this adaptive transmission interval control protocol will be discussed in detail in Chapter 6.

5.3.2 Results

A.   Mean Absolute Percent Error (MAPE)

In a decentralized traffic information system, the travel time information of a road segment is distributed among vehicles during their traveling in the traffic network. At any point in time, the travel time estimate of a road segment for a specific period in all vehicles' database can be viewed as a random variable that varies with time and space.

For instance, using the third algorithm described in Section 5.2.3, every time there is a vehicle reaching the endpoint of a road segment during period from 7:00AM to 7:10AM, the travel time estimate of the segment for that period will be updated by that vehicle using equation (5.2). Thus the estimated value will vary from time to time and the closer a vehicle is to the segment, the newer the estimate value will be in its database. After 7:10AM, the estimate for that period of time will not change any more. As time goes by, the estimated value in the database of the vehicles in the network will converge to the final estimated value. To indicate the accuracy of the estimate value in all vehicles' database, we define a mean absolute percent error (MAPE) to represent the error between the estimate and ground truth (which is known directly from the traffic simulation). It can be expressed as the average absolute percentage difference between the estimate and ground truth:

$$MAPE = \frac{1}{n} \sum_k \left| \frac{\hat{t}_{k,(t_1,t_2)}(i) - t_{g,(t_1,t_2)}(i)}{t_{g,(t_1,t_2)}(i)} \right| \tag{5.3}$$

where

n is the total number of vehicles whose database include the travel time estimate of road segment i;

$\hat{t}_{k,(t_1,t_2)}(i)$ is the travel time estimate of road segment i during the interval (t_1,t_2) in kth vehicle's database;

$t_{g,(t_1,t_2)}(i)$ is the ground truth of travel time for road segment i during the interval (t_1,t_2).

Table 5.1 Comparison with MAPE with Penetration Rate 10% (Total Link = 511)

Algorithm	The percentage of links with MAPE < 10%	The percentage of links with MAPE < 20%
Blind Averaging	73.4	93.2
Averaging with a decay factor	85.3	97.7
Estimating only by direct-experiencing vehicles	96.7	99.2

From the results shown in Table 5.1, we can see that approximately 73.4%, 85.3% and 96.7% of the links in the simulation network during period between 7:40AM and 7:50AM have estimated average speed with mean absolute percent error less than 10% by using directly averaging by all participating vehicles, estimating with decay factor, and the estimation technique using only direct experienced vehicles respectively. The scheme that estimates only by the participating vehicles that experienced the link has significant improvement in estimation accuracy as described in Section 5.2.3.

B. Histogram of Average Link Travel Time

Why does the algorithm of directly averaging by all participating vehicles show poor performance? To understand this better, we have chosen a random link (Link 657) to explain the problem from which the algorithm suffers - the values of early generated travel time dominate the final estimate value.

The summary data for link 657 is shown in Table 5.2. Figure 5.5 shows the observations of travel time and its histogram for link 657 during the period between 7:40AM and 7:50AM. The top graph of Figure 5.5 gives the observation of travel time for all vehicles that traverse the link 657 during that period. The ground truth value is

then obtained by averaging all these values (approximately 20 seconds). The bottom graph of Figure 5.5 is the observation of travel time corresponding to a 10% penetration rate. The value in the lower portion of Figure 5.5 is a subset of those in the upper graph if it is assumed that only a fraction of vehicle has inter-vehicle communication capability.

Table 5.2 Summary Data for Link 657

Link No.	Ground truth (GT)	Min. Travel Time	Max. Travel Time	Percentage of observations outside $1 \pm 10\%$ of GT (%)	Mean of Estimate	Error Percentage of estimation values (%)
657	20.0	15.0	27.0	13.5	15.6	28.4

The graphs in Figure 5.6 show the distribution of average link speed for Link 657 at different times in the simulation. The first time was recorded at 07:40:30 with other snapshots taken at 30 second intervals (proceeding left to right, then down). From the bottom graph of Figure 5.5, it can be seen that the first two values are below the ground truth. When the third vehicle exits the link at t = 7:40:24, the estimate values of the link in the database of all vehicles around it are calculated by the first two values. Even though the value that experience by the third vehicle is greater than the true value, since the estimate values are dominated by the first two values, it has little effect on the new updates of the estimate. This can be shown by the first graph of Figure 5.6. This makes the mean of the link average value in vehicles' database extend well below the true value. Moreover, in the blind averaging scheme, the estimated values not only depends on link traffic conditions (e.g, the flow of the analyzed link), but also on the traffic conditions of all other links that have driven on by vehicles whose database include the information of

the analyzed link. This makes it difficult the build up an analytical model for the algorithm.

Figure 5.5 Histogram of travel time of Link 657. Upper graph contains data from all vehicles in the simulation. Lower graph contains data from a random 10% sample of the vehicles.

Figure 5.6 Histograms of estimated link travel time at different times in the simulation, starting at 7:40:30 with further snapshots at 30 second intervals, proceeding left to right, then down.

Chapter 6
Adaptive Dissemination Mechanism

One of the key challenges in a decentralized network approach is how to disseminate information between vehicles. The environment is highly dynamic and the density of vehicles can vary from only a few vehicles per kilometer-lane to upwards of 300 vehicles per kilometer-lane in traffic jam situations. Furthermore, in decentralized traffic information systems, the data collection, processing, and dissemination lies entirely with each individual vehicle; there is no centralized processing center. Each individual vehicle can estimate traffic conditions based on the traffic information sensed by itself and that received from its neighbors. Thus the design of the dissemination scheme is crucial so that information is readily available for traffic estimation.

In this chapter, two adaptive dissemination mechanisms are proposed for inter-vehicle communications. In the first proposed design, each participating vehicle can adapt its transmission interval according to the current traffic speed and also disseminate the traffic information of different roadway segments at different rates according to the distance from its current position. This scheme is very suitable to information transmission in a decentralized traffic information systems and we is used in our system. In the second scheme, each node can adapt both their transmission power and

transmission interval according to the local environment. This scheme can be used to transmit more general information, for example vehicle control and operation information in Automated Vehicle Control and Safety Systems.

6.1 Communication Bandwidth Analysis

Since 802.11a has initially been selected by the DSRC standard committee as the MAC layer protocol, it is assumed that the IEEE 802.11 broadcast mode is used as the wireless interface for inter-vehicle communication in our analysis. In this DSRC standard, a wireless link is expected to have a maximum "line-of-sight" range of 900 meters. In order to design a communication protocol that can ensure the efficient information exchange among vehicles, it is necessary to analyze the maximum communication bandwidth required by the system.

Most of the current research on vehicle ad-hoc networking assumes a simplified radio transceiver model. In the model used in this analysis, a circular transmission range centered at the transmitter is defined, based on a certain transmission power and noise level, such that any node inside the range can receive any packet from the transmitter. When a receiver is within the transmission range of two transmitters that are transmitting simultaneously, the packets are assumed to interfere with each other, leading to a collision at the receiver, such that no packet is received successfully. Carrier sensing can reduce the number of packet collisions. Often it is assumed that the carrier sensing range is equal to the transmission range, which can contribute to the hidden terminal problem

[14]. Ideally the hidden terminal problem can be avoided if the sensing range is two times the transmission range.

It is assumed that the road under study has two-way directional traffic with average densities d_1, d_2 and average velocities v_1, v_2 for each direction respectively. Let p be the penetration rate of vehicles equipped with inter-vehicle communication capability. The transmission range of a vehicle is R and the sensing range is $2R$, then the number of participating vehicles inside its sensing range is given as

$$n_v = 4pR \cdot (d_1 + d_2).$$ (6.1)

According to common traffic theory, the speed-density relationship of a freeway can be estimated as a linear function [15]:

$$v = v_f - v_f \cdot \frac{d}{d_m}$$ (6.2)

where v_f is the free flow speed and d_m is the maximum density.

Suppose k is a value greater than the ratio of maximum velocity to average velocity of a road segment. A transmission interval that is not greater than $\dfrac{2R}{k \cdot (v_1 + v_2)}$ is sufficient to recognize and inform other vehicles. Thus in the case that there are L lanes in each direction of the road, the total packet number can be calculated as:

$$
\begin{aligned}
n_p &= \frac{n_v L}{T_i} = 4pR \cdot (d_1 + d_2) \cdot L \cdot \frac{k(v_1 + v_2)}{2R} \\
&= 2kp \cdot (d_1 + d_2) \cdot [2v_f - v_f \frac{(d_1 + d_2)}{d_m}] \cdot L \\
&= -\frac{2kp \cdot v_f \cdot L}{d_m} \cdot [(d_1 + d_2)^2 - 2d_m \cdot (d_1 + d_2)]
\end{aligned}
$$ (6.3)

It can be seen that the total number of packets is independent of the transmission range R and it has the maximum value of:

$$n_{p\max} = 2pkv_f d_m L \qquad (6.4)$$

when $(d_1 + d_2) = d_m$.

6.1.1 5.9GHz 802.11a Channels

In the real-world, inter-vehicle communication will not always be line-of-sight; DSRC channels will suffer from multi-path effects like other radio frequency bands. Due to multi-path and different attenuation effects, the signal amplitude at a given distance can be treated as a random variable and both the transmission range and sensing range won't be exactly circular. Several studies (e.g. [16, 17]) have demonstrated that the distribution of a signal amplitude x at a given distance in wireless channels can be accurately described by the two-parameter Nakagami distribution:

$$f(x;\Omega,m) = \frac{2m^m x^{2m-1}}{\Gamma(m)\Omega^m} \cdot \exp\left(-mx^2/\Omega\right),$$
$$x \geq 0, \Omega > 0, m \geq 1/2 \qquad (6.5)$$

where Ω is the second moment of the distribution and is interpreted as the average power gain and m is considered as the "shape" or the "fading" parameter. The larger the value of m, the lower the variation of power around the mean. For m equal to 1, we get a Raleigh distribution, which is found to adequately model the channel gain amplitude in the absence of the line-of-sight signal. In [18], the authors studied the channel characteristics of typical highway environment. Their results show that there is no clearly

discernible distance-dependence trend in the values of *m* and the value of *m* often falls between 0.5 and 1 for a highway environment. The value of Ω depends on the sender-receiver distance.

Up to a certain distance (referred to as the cross-over distance), Ω decreases as an inverse-square function of distance, as described by the free space model [19]:

$$\Omega(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{6.6}$$

where P_t is the transmitted signal power. G_t and G_r are the antenna gains of the transmitter and the receiver respectively. $L(L \geq 1)$ is the system loss, h_t and h_r are transmitter and receiver antennae heights respectively and λ is the signal wavelength. After the cross-over distance, Ω decreases much more rapidly as an inverse-fourth power of distance, as predicted by the two-ray model [19]:

$$\Omega(d) = \frac{P_t G_t G_r h_t^2 h_r^2}{d^4 L} \tag{6.7}$$

At the cross-over distance, the two model give the same result. So The theoretical cross-over distance d_c can be calculated as

$$d_c = \frac{4\pi h_t h_r}{\lambda} . \tag{6.8}$$

For the analysis in this paper, the theoretical probability of successful reception and sensing along the sender-receiver distance is calculated using the parameter values listed in Table 4.1 in Chapter 4. The *m* value is set to 0.75.

6.1.2 Required Bandwidth

As illustrated in Figure 6.1, a successful reception rate of approximately 93% is achievable at 500 meters and a successful sensing rate is approximately 95% at 1000 meters. Considering these reception failure and sensing failure rates, when a vehicle sends a packet, other vehicles within the range $R = 500$ meters will have a probability greater than 92% that they will correctly receive it. Suppose that $P(x)$ is the probability of successful sensing at distance x, then in the channel fading model the average number of packets that can be sensed by a vehicle can be given as:

$$
\begin{aligned}
n_p{}' &= 2\int_0^\infty \frac{n_v LP(x)}{T_i} dx \\
&= 2\int_0^\infty d_1 + d_2)pLP(x)\frac{k(v_1 + v_2)}{2R} dx \\
&= \frac{\int_0^\infty P(x)dx}{2R} \cdot kp(d_1 + d_2) \cdot [2v_f - \frac{v_f}{d_m}(d_1 + d_2)] \cdot L
\end{aligned} \tag{6.9}
$$

The maximum number of packets is given as $n_p{}'_{\max} = \dfrac{\int_0^\infty P(x)dx}{R} pkv_f d_m \cdot L$, when $(d_1 + d_2) = d_m$. For a typical freeway environment with a design speed of 70 miles/hour, maximum density of 130 vehicles/mile, and four lanes in each direction, $n_p{}'_{\max}$ is approximately 61 packets/second when k is set to be 1.5 in the extreme case when all vehicles are participating in inter-vehicle communication and the channel model parameters are set as shown in Table 6.1. Assuming that the information in each cell in the spatio-temporal traffic information database can be represented by three bytes, the size of the database will simply be 18 bytes times the number of links in the network.

Even with a large network with thousands of road segments, the total size of the database is very manageable. For example, if 1000 road segments are contained in a vehicle's database, the bandwidth required for each vehicle is approximately 150 kbps. In the case when $n_p{}'$ is at its maximum value, the total required bandwidth is approximately 9.1 Mbps. DSRC has a typical data transmission rate of 27 Mbps, thus the packet load in such a network will not exceed the channel capacity.

Since each car's transmission interval changes based on current link speeds, the required communications bandwidth is minimized when a vehicle exchanges its traffic information database. In order to show how well the proposed scheme reduces the required bandwidth, it can be compared to the bandwidth requirements if the vehicle's traffic information is broadcasted periodically with a static transmission interval. In the periodic transmission scheme, the average number of packets that can be sensed by a vehicle in the channel fading model is given as:

$$
\begin{aligned}
n_p{}'' &= 2\int_0^\infty \frac{n_v LP(x)}{T}\,dx \\
&= 2\int_0^\infty (d_1 + d_2)\,pk(v_1 + v_2)\frac{LP(x)}{2R}\,dx \qquad (5.10) \\
&= 2\left[\int_0^\infty P(x)\,dx\right]\frac{(d_1 + d_2)pL}{T}
\end{aligned}
$$

(a)

(b)

Figure 6.1 Probability of (a) reception and (b) sensing at distance *d* when no interference is present.

It is assumed that the freeways have a design speed of 70 miles/hour, maximum density of 130 vehicles/mile, and four lanes in each direction. Therefore, an interval of T = $10s$ is sufficient to recognize and inform any vehicle and n_p'' is maximized when $d_1 = d_2 = d_m$. Thus, the corresponding required bandwidth for the periodic transmission scheme is 39 Mbps, which is approximately 4.3 times of that for the adaptive scheme.

6.2 Adaptive Interval Control Broadcast for Traffic Information Distribution

In Chapter 5, a variety of travel time estimation techniques were evaluated for an IVC-based traffic information system scenario. Due to the decentralized characteristics of such a system, it was shown that a well-designed estimation algorithm is necessary to meet overall travel time accuracy requirements of the system. There are several decentralized estimation techniques that do not converge to a correct representation of travel times across the roadway network. As described in Chapter 5, one technique that does perform well is as follows: Each IVC-equipped vehicle calculates its own link travel times (using position and velocity information from its GPS receiver and having a database of link end points) and periodically broadcasts its travel time spatio-temporal database to other vehicles. Other vehicles will receive this information and will include new data into their own spatio-temporal database. The information update is done on a link-by-link basis using a running average technique. However, data on a particular link will only be updated once from a vehicle that directly experiences the travel time along that link. This way there is no averaging weight bias in the final estimate of link travel

times. To ensure that direct observations can be counted as samples to the final estimate for corresponding links, it is also important for each vehicle to transmit the traffic information of the adjacent several links at an interval much less than $\dfrac{2R}{k \cdot (v_1 + v_2)}$.

Based on the previous analysis, in a typical traffic scenario with the specified wireless interface parameters setting, if a vehicle transmits packets at an interval less than $\dfrac{2R}{k \cdot (v_1 + v_2)}$, then it will be possible to have successful communication with any IVC-equipped vehicle running in the opposite direction and the required bandwidth will be much lower than the channel capacity. Thus in this scheme, every IVC-equipped vehicle broadcasts its data at a certain interval specified as the transmission interval t_i. At the beginning when the vehicle enters the network, the transmission interval is set to $\dfrac{2R}{k \cdot (v_1 + v_2)}$, where v_1 and v_2 are the average speed of the vehicle traveling on that particular link. Later v_1 and v_2 are set to space-mean averages once link travel times are received from other vehicles or measured by the vehicle itself. Given the link travel time estimate $t(i)$, it is possible to derive the space-mean average velocity from $v(i) = \dfrac{t(i)}{l(i)}$ where $l(i)$ is the length of the segment in the network database. Figure 6.2 shows the pseudo-code for this dissemination scheme.

```
Function Estimating_DecayFactor()
{
    S₀:  the road segment that the vehicle is traveling
    S₁:  the adjacent road segments
    tᵢ₁: the transmission interval to transmit traffic information of road
    segments S₁
    t₁:  the time elapsed since last transmission for traffic information
    of road segments S₁
    S₂:  the other road segments
    tᵢ₂: the transmission interval to transmit traffic information of road
    segments S₂
    t₂:  the time elapsed since last transmission for traffic information
    of road segments S₁
    eₑ: The event that the vehicle exits the road segment S₀

    if (eₑ)
        transmit_information(S₀)
    end

    if (t₁ == tᵢ₁)
        transmit_information(S₁)
    end

    if (t₂ == tᵢ₂)
        transmit_information(S₂)
    end

}
```

Figure 6.2 Pseudo-code for proposed dissemination scheme

6.3   Simulation Results

In this study, we still use the integrate simulation environment discribed in section

Chapter 4, which is based on the microscopic traffic simulator – PARAMICS.

Figure 6.3 A simple scenario: Ideal highway conditions

We consider a simple scenario with a straight highway as shown in Figure 6.3. The simulated highway is 15 miles long with 3 lanes in each direction and has no entrances and exits. Suppose that q_1 and q_2 represent traffic flow in the two directions of traffic. The traffic from right to left (with flow q_2) is simulated under six different levels-of-service (LOS). Similarly, the traffic in the opposite direction (with flow q_1) is also simulated under six different LOS values. All combinations are examined. The LOS conditions for the traffic range from a flow rate of 600 vehicles/hour to 2000 vehicles/hour with an interval of 200 vehicle/hour. This is accomplished by adjusting the travel demand inputs (i.e., origin/destination matrix) and other parameters within the PARAMICS simulator. Based on the simulation runs, traffic statistics for the different levels of service (and corresponding speed) are given in Table 2.1.

We define a *sample rate* measure as the ratio of the number of travel time samples that contribute to the average estimate travel time to the total number of participating vehicles that pass the studied road segment in direction 1. Figure 6.4 shows this sample rate measure under different traffic flow conditions. The results of Figure 6.4(a) are obtained when all traffic information is transmitted at the same constant rate $2R/[k \cdot (v_1 + v_2)]$. In contrast, Figure 6.4(b) shows the results when the traffic information of

the links within a limited range (e.g., three miles of the vehicle's current position) is transmitted every second and the traffic information for the other links is transmitted at the rate $2R/[k \cdot (v_1 + v_2)]$. It can be seen that the result for the second solution is better, especially in the case when the traffic flow in the opposite direction is low.

(a)

(b)

Figure 6.4 Sample rate measure (ratio of the number of travel time samples that contribute to the average estimate travel time to the total number of participating vehicles that pass the studied link) under different traffic flow conditions for two scenarios. (a) without local frequent transmission; b) with local frequent transmission.

6.4 A Transmission-Interval and Power-Level Modulation Methodology

Supposed L is the link length and R_i is the transmission radius as shown in Figure 2. Since a vehicle will only transmit a packet if there aren't any transmissions in its transmission radius, only one vehicle will transmit within this neighborhood. Consequently, the maximum throughput T_{max} is given by equation (6.11), where B_r is the transmission rate of each vehicle.

$$T_{max} = B_r * L / (2 * R_i) \tag{6.11}$$

Since the transmission radius is proportional to the radio range, which is determined by transmission power, reducing the radio range can help to increasing the network throughput. However reducing the radio range to certain extent will also cause network fragmentation and increase the delay in message propagation.

Let n be total number of vehicles in L length link, λ be the bit generation rate for each vehicle, d be the traffic density, T_i be transmission interval and p be average size for each broadcast packet, then we also have the following equations:

$$n\lambda \le T_{max} \tag{6.12}$$

$$n = L \cdot d \tag{6.13}$$

$$\lambda = \frac{1}{T_i} \cdot p \tag{6.14}$$

From equations (6.12) to (6.14), we can see that to meet the communication needs, one can either reduce transmission power to increase throughput or increase transmission interval to decrease the required information distribution in a high traffic density situation. However, increasing transmission interval and decreasing transmission range will increase the delay and the risk of missing communication opportunities when a vehicle passing by at a high relative velocity. Therefore, both transmission power and transmission interval need to be adapted according to the local traffic and communication circumstance to distribute traffic information efficiently.

Figure 6.5 Vehicle layout on roadway with variable transmission radius.

6.4.1 Methodology

From the above analysis, it is apparently that transmission power and transmission interval have important impacts on system performance. As a result, we have designed an adaptive power and interval control broadcast protocol for the efficient distribution of traffic information as described in the previous section. In general, vehicles will reduce their transmission power in high density traffic regions, thereby reducing the number of

nodes inside their transmission range. Also under high-density conditions, vehicles can simultaneously increase their transmission interval (i.e., decrease the frequency), thereby reducing packet collisions. On the flip side, vehicles can increase their transmission power and decrease their transmission interval (increase frequency) in low-density traffic conditions, thereby reducing propagation delay and the risk of network fragmentation.

In Chapter 2, we introduced the concept of LOS, which can be used as a means of describing the quality of traffic operations within a traffic stream and at a given location. Six LOS are defined using letter designations for each level, from A to F, with LOS A representing the best operating conditions and LOS F the worst. In general, LOS can be related to an average speed with respect to the link design speed. Thus, if a vehicle knows its average speed over a link, it can roughly estimate its LOS. In terms of transmission power and interval parameters, it is possible to roughly set these parameters based on the rough estimates of LOS and the relationships given in Figure 2.6.

In our proposed methodology, a vehicle's transmission/reception status is also used to adjust the transmission parameters. We define two measurements of transmission/reception history. The first one is the transmission attempt failure rate, R_{tf}. This can be calculated by dividing the number of transmission attempt failures by the total number of transmissions of each vehicle. The other measure is successful packet receipt rate, R_{rs}. Analogously, R_{rs} can be obtained by dividing the number of successfully received packets by the total number of received packets. As vehicle density increases, the possibility of packet collisions will also increase, which will raise the

transmission and receiving failure rate. When R_{tf} exceeds the upper threshold ΔR_{thupl} or R_{rs} is lower than its lower threshold ΔR_{rsl} (meaning that the channel is congested) the vehicles reduce their transmission power or increase their transmission interval. Otherwise, if R_{tf} is lower than the lower bound ΔR_{thl} or R_{rs} exceeds the upper threshold $\Delta R_{r\sup}$, the vehicles will increase its transmission power or increase its transmission interval.

6.4.2 Simulation Setup and Results

The topology of the freeway used in this study is straightforward (as shown in Figure 6.5). The simulated road is 3 miles long with 3 lanes in each direction and has no entrances and exits. We simulate the traffic scenario under six different LOS for an ideal freeway by adjusting the travel demand inputs (i.e., origin/destination matrix) and other parameters within PARAMICS. The standard IEEE 802.11 MAC protocol was used for medium access with the frequency set to 5.9GHz. The Channel Bit Rate was set to 54Mbps. The maximum transmission range is set to be 500 meters, using an omni-directional antenna at a height of 1.5 meters.

One of the important parts in our protocol is that each vehicle roughly set up the transmission power and interval according to the current link LOS. Thus in the simulation we first estimate the optimal transmission power and transmission interval for the traffic situation in each different LOS. Then each vehicle can roughly set its transmission parameters according to the current estimated link LOS. We define Average Package Successfully Received Rate (ASRR) for each vehicle as the rate of packets that a

vehicle can receive successfully. Here it is used to evaluate efficiency of traffic information distribution.

In Figure 6.6 - 6.11, the five curves in each graph correspond to the average successfully received rate or the total number of successfully receiving vehicles of a packet when transmission interval is set to be 0.2, 0.5, 0.7, 1.0 and 1.5s respectively. It is obvious that decreasing interval will reduce the ASRR since more packages will be transmitted in unit time, which causes more collision and the increase of package drop rate. Increasing transmission power will decrease ASRR since more vehicles are included within the transmission range of a vehicle and thus more collisions will happen.

Because the traffic analysis in each vehicle in a decentralized self-organizing traffic information system depend on the information obtained from its surrounding vehicles, thus the average successfully received rate of a packet should be high to ensure the efficient distribution of traffic information and the accuracy of the estimation for traffic information. According to Figure 6.5, within transmission range, the nodes that are distant to the transmitting node have high risk of collision than those close to the transmitter. Thus low average successfully received rate will cause low efficiency of the distribution of traffic information. For example, if we require average successfully received rate to be at least 0.8 to ensure the efficient distribution of traffic information and the accuracy of the estimation for traffic information. We can see that the transmission power can be set to be the maximum value for LOS A, B, C, which is 500 meters, due to the low traffic density. For LOSA, the minimum transmission interval is between 0.2s and 0.5s. It is between 0.7 and 1.0s for LOSB and between 1.0s to 1.5s for

LOSC. For LOS D, the maximum transmission range that can be set is 400 meters and the minimum transmission interval is 1.5s. While for LOS E, the maximum transmission range can only be set to be 220 meters and the minimum transmission interval is also 1.5s. We could observe that the simulation results match analytical results.

Figure 6.6 Average Successfully Received Rate (ASRR) for each packet under LOS A

Figure 6.7 Average Successfully Received Rate (ASRR) for each packet under LOS B

Figure 6.8 Average Successfully Received Rate (ASRR) for each packet under LOS C

Figure 6.9 Average Successfully Received Rate (ASRR) for each packet under LOS D

Figure 6.10 Average Successfully Received Rate (ASRR) for each packet under LOS E

Thus for each vehicle, the associated transmission parameters, such as transmission power and transmission interval, can be set according to current LOS, which can be estimated according to its relationship with link travel speed. As we described before, transmission parameters can also be adjusted to correspond to more precise communication environment according to current transmission/reception status, which are transmission attempt failure rate, R_{tf} and successful packet receipt rate, R_{rs}. Figure 6.11 shows the performance comparison among Transmission Interval control, Transmission Power control, and Adaptive transmission power and interval control protocol. Here we define Average Number of Receiving Vehicle (ANRV) as the total number of vehicle that receive at least one packet from the transmitting vehicle when it traverses the link. From the figure we can see that the adaptive transmission power and interval control scheme shows the highest ANRV among the three control schemes.

Figure 6.11 ANRV versus LOS

6.5 Simulation Results of Overall System Performance

In this section, the simulation results of the performance of the overall system, which uses the traffic estimation algorithm and adaptive interval control broadcast dissemination scheme discussed in Chapter 5 and this chapter respectively, is discussed. We use the same traffic network shown in Figure 5.4 in the following simulation runs.

6.5.1 Mean Absolute Percent Error (MAPE)

We have defined MAPE in Chapter 5 and have used this in determining the average absolute percentage difference between the estimate and ground truth. This measure can be used to represent the travel time estimation accuracy of the proposed decentralized traffic information system. We use the probability that MAPE in travel time is within 10%, $P_r\{MAPE < 0.1\}$, to evaluate the accuracy of the system. Figure 6.12 plots the level of accuracy versus traffic flow with different penetration rates of 3%, 5%, and 10%. It is clear that the level of accuracy increases rapidly with increased traffic flow and quickly approaches 100% even with a small penetration rate. The accuracy of the travel time estimate increases with increasing penetration rate or traffic flow. For traffic flow greater than 500 vehicle/hour/lane (corresponding to flow with 1500 vehicle/hour/link in Figure 6.12), an IVC-equipped vehicle penetration rate of 5% can achieve more than 90% accuracy (the mean absolute percent error of the estimated speed of a link is less than 5%) in terms of an effective traffic information system.

Figure 6.12 Accuracy of travel time estimate versus traffic flow with different penetration
rates

6.5.2 Speed of Information Dissemination

One of the key concerns in an IVC-based traffic information system is how quickly
can information spread throughout the network. To better understand this, a variety of
simulation runs were conducted with different penetration rates of IVC-equipped vehicles
and different traffic densities. As an example, the scenario with a 10% penetration rate
and normal freeway traffic flow at 7:40AM is shown in Figure 6.13 – 6.16. In this figure,
road segment 508 (identified as "*" roughly in the center of the map) is traversed by a
single vehicle at 7:40AM. The 7:40AM link 508 travel time information is then tracked
through the system at different time intervals. In Figure 6.11, 6.12, 6.13, and 6.14,
snapshots are taken at 10 minute intervals, i.e., 7:50AM, 8:00AM, 8:10AM, and 8:20AM
respectively. The dark road segment lines in the figure represent the dissemination range

of the travel time estimated. It can be seen that the information propagates to a region of size about 20 km within 10 minutes, and the majority of the region is covered in approximately 20 minutes. The speed of dissemination increases with increased penetration rate of IVC-equipped vehicles and increased traffic density. There were no observed differences on how quickly information spread based on which averaging technique was used.

Figure 6.13 The dissemination of link 508 (7:40AM) travel time at 7:50AM (Black represents the area with link 508 travel time known)

Figure 6.14 The dissemination of link 508 (7:40AM) travel time at 8:00AM (Black represents the area with link 508 travel time known)

Figure 6.15 The dissemination of link 508 (7:40AM) travel time at 8:10AM (Black represents the area with link 508 travel time known)

Figure 6.16 The dissemination of link 508 (7:40AM) travel time at 8:20AM (Black represents the area with link 508 travel time known)

Chapter 7

Analytical Modeling

In the decentralized traffic information solution, the effectiveness of the system depends on the number of vehicle participating in the system. Moreover the density of participating vehicles in an area may vary dramatically with time and space. An analytical model has been developed to examine the effect of the key parameters on the system performance. The model characterized the system as a traffic stream with randomly distributed participating vehicles. It is assumed that participating vehicles are independent and randomly distributed among vehicles in the traffic stream. Each participating vehicle records the traversal time for a link, estimates the travel time, and sends the value to its surrounding vehicles as soon as it exits the link. Each vehicle shares its database information at a particular interval (transmission interval), which is determined according to the current average speed in both directions and channel occupancy rate.

7.1 Distribution of Participating Vehicles

Given a flow Q vehicle per hour, the number N of vehicles that traverse a road segment during time interval t_i seconds follows a Poisson distribution with mean $\dfrac{Q \cdot t_i}{3600}$

[15]. For each of these N vehicles, it assumed that there is a probability p that it is equipped the on-board integrated device. The number of equipped vehicles X that traverse the road segment during time interval t_i, given total N vehicles, has a binomial distribution

$$P\{X = x \mid N = n\} = \binom{n}{x} p^x (1-p)^{n-x} \qquad 0 \le x \le n \tag{7.1}$$

The unconditional probability of X is:

$$P(X = x) = \sum_{n=0}^{\infty} P\{X = x \mid N = n\} \cdot P\{N = n\}$$

$$= \sum_{n=x}^{\infty} \frac{n!}{(n-x)! \cdot x!} \cdot p^x (1-p)^{n-x} \cdot \frac{e^{-\frac{Qt_i}{3600}} \cdot (\frac{Qt_i}{3600})^n}{n!} \tag{7.2}$$

$$\overset{k=n-x}{=} \frac{e^{-\frac{Qt_i}{3600}}}{x!} \cdot (\frac{Qt_i p}{3600})^x \sum_{k=0}^{\infty} \frac{[\frac{Qt_i}{3600} \cdot (1-p)]^k}{k!} = \frac{e^{-\frac{Qt_i p}{3600}} \cdot (\frac{Qt_i p}{3600})^x}{x!}, \qquad x \ge 0$$

Thus X also follows a Poisson distribution with mean $\dfrac{Qt_i p}{3600}$. The travel time of a road segment is unknown if no instrumented vehicle traverses the segment during time interval t_i. The probability of at least one vehicle traversing a road segment (in the other words, a segment's travel time is known during time interval t_i) is

$$P\{X > 0\} = 1 - e^{-\frac{Qt_i p}{3600}} \tag{7.3}$$

We can see from Figure 7.1 that even in the case that the penetration rate is very small, a small flow rate can ensure at least one equipped vehicle with probability of 90%.

Figure 7.1 Probability of at least one equipped vehicle in the traffic stream.

7.2 Information Dissemination

In our system design, each vehicle updates the estimate of average travel time of a road segment by using the traversal time experienced by itself and the estimate value stored in its database and sends it to its neighbor as soon as it exits the segment. It is important that this updated estimate can be forwarded to the next equipped vehicle in the same road segment, otherwise this sample of traverse time will not be counted to the final estimated value. In the following analysis, we consider the probability of an estimate being received by the next participating vehicle before it reaches the endpoint of the link in several different cases. In each case, we suppose that d_{h1} is the distance headway between a vehicle and the next participating vehicle and d_{h2} is the distance headway

between the first participating vehicle that haven't reached the endpoint of the segment in the opposite direction and the participating vehicle in front of it (Figure 7.2).

Case 1: $d_{h1} \leq R$

In this case, the distance between two consecutive participating vehicles is within the transmission range (Figure 7.2 (2)). Thus the updated estimate transmitted by the preceding vehicle as soon as it exits a road segment, can be received by the next equipped vehicle. The probability can be express as

$$P\{d_{h1} \leq R\} = P\{t_{h1} \cdot \bar{v}_1 \leq R\} = P\{t_{h1} \leq R/\bar{v}_1\} = 1 - e^{-\frac{QpR}{3600\bar{v}_1}} \tag{7.4}$$

Case 2: $d_{h2} \leq 2R$

In this case, when a vehicle transmits its updated estimate immediately after it exits the road segment and, there are always at least one vehicle within the transmission range in the opposite direction, which helps to forward the estimate to the next participating vehicle before the next participating vehicle exits the segment (Figure 7.2 (3)). The probability can be expressed as:

$$P\{d_{h2} \leq 2R\} = P\{t_{h2} \cdot \bar{v}_2 \leq 2R\} = P\{t_{h2} \leq 2R/\bar{v}_2\} = 1 - e^{-\frac{QpR}{1800\bar{v}_2}} \tag{7.5}$$

Case 3: $d_{h1} > R$, $d_{h2} > 2R$ *and* $t_r < t_{h1}$

We define the receiving time, t_r, as the time it takes for vehicle to obtain the estimate updated by the vehicle ahead of it in the same segment. From Figure 6.2 (4), we can see that vehicle A will pass the travel time estimate to vehicle C when they move towards each other and vehicle C will forward the information to vehicle B later on. The distance between vehicle B and C at the time when vehicle A reaches the endpoint of the segment will be less than $d_{h1} + d_{h2} - R$. We know if t_r is less than the time headway t_{h1} in this

case, the estimate can still be received by the next participating vehicle before it exits the segment. In this case,

$$t_r \leq \frac{(d_{h1} + d_{h2} - R) - R}{\bar{v}_1 + \bar{v}_2} = \frac{d_{h1} + d_{h2} - 2R}{\bar{v}_1 + \bar{v}_2} \qquad (7.6)$$

Figure 7.2 Dissemination cases of the traffic information to the next participating vehicle

The probability that an estimate cannot be received by the next participating vehicle before it exits the link is:

$$P\{t_{h1} < t_r \mid d_{h1} > R, d_{h2} > 2R\} < P\{t_{h1} < \frac{d_{h1} + d_{h2} - 2R}{\bar{v}_1 + \bar{v}_2}\}$$

$$= P\{t_{h1} < \frac{t_{h1}\bar{v}_1 + t_{h2}\bar{v}_2 - 2R}{\bar{v}_1 + \bar{v}_2}\} = P\{t_{h2} - t_{h1} > \frac{2R}{\bar{v}_2}\} \tag{7.7}$$

We know that both t_{h1} and t_{h2} follow an exponential distribution with mean $\bar{t}_1 = \dfrac{3600}{Q_1 p}$ and $\bar{t}_2 = \dfrac{1800}{Q_2 p}$ respectively. Thus $t_{h2} - t_{h1}$ follows the following distribution:

$$p(t) = \frac{1}{\bar{t}_1 + \bar{t}_1} e^{\frac{t}{\bar{t}_1}} u(-t) + \frac{1}{\bar{t}_1 + \bar{t}_1} e^{-\frac{t}{\bar{t}_2}} u(t) \tag{7.8}$$

Thus

$$P\{t_{h2} - t_{h1} > \frac{2R}{\bar{v}_2}\} = \frac{\bar{t}_2}{\bar{t}_1 + \bar{t}_2} e^{-\frac{t}{\bar{t}_2}} \tag{7.9}$$

The probability that an estimate can be received by the next participating vehicle before it exits the segment can be calculated as below.

$$P_s = 1 - P\{t_{h1} < t_r \mid d_{h1} > R, d_{h2} > R\} P\{d_{h1} > R\} P\{d_{h2} > R\}$$

$$= 1 - \frac{\bar{t}_2}{\bar{t}_1 + \bar{t}_2} e^{-\frac{t}{\bar{t}_2}} \cdot e^{-\frac{Q_1 p R}{3600\bar{v}_1}} \cdot e^{-\frac{Q_2 p R}{3600\bar{v}_2}}$$

$$= 1 - \frac{Q_1}{Q_1 + Q_2} e^{-\frac{Q_2 p R}{1800\bar{v}_2}} e^{-\frac{Q_1 p R}{3600\bar{v}_1}} \cdot e^{-\frac{Q_2 p R}{3600\bar{v}_2}} \tag{7.10}$$

Figure 7.3 Probability of an estimate being received by next participating vehicle before it reaches the endpoint of the road segment

Figure 7.3 shows the effects of traffic flow rate of both directions on the probability that a vehicle in a road segment can receive the estimate updated by the vehicle ahead of it in the same segment. We can see even when the flow rate is small (e.g. $Q_2 = 700$), an estimate still has 86% probability to be received by the next participating vehicle in the same segment.

7.3 Travel Time Estimates

We assume that the fleet travel time t of a road segment has a distribution with mean $E[t] = t_\mu$ and variance $Var[t] = \sigma_t^2$. The estimate of mean travel time of the link during time interval t_i from x samples ($x \geq 1$) is $t_d = \dfrac{t_1 + t_2 + \cdots + t_x}{x}$, where $t_1, t_2, \cdots, t_x$ are the travel times of each equipped vehicle to traverse the link during period t_i. Since $t_1, t_2, \cdots, t_x$ are samples from same sample space, they are independent and have identical

distribution as t. Therefore the conditional mean of t_d, given x vehicles traversing the link, is

$$E[t_d \mid x] = E[\frac{t_1 + t_2 + \cdots + t_x}{x}]$$
$$= \frac{E[t_1] + E[t_2] + \cdots + E[t_x]}{x} = \frac{x \cdot E[t]}{x} = t_\mu$$

(7.11)

Therefore $E[t_d \mid x]$ is independent of x and the unconditional mean of t_d is also equal to t_μ. Therefore

$$E[t_d] = E[t_d \mid x] = t_\mu$$

(7.12)

The conditional variance of t_d, given x vehicles traversing the link, is

$$Var[t_d \mid x] = Var[\frac{t_1 + t_2 + \cdots + t_x}{x}]$$
$$= \frac{Var[t_1] + Var[t_2] + \cdots + Var[t_x]}{x^2} = \frac{x \cdot Var[t]}{x^2} = \frac{\sigma^2}{x}$$

(7.13)

In the previous discussion, we know that if given a flow Q vehicle per hour and the penetration rate p, the number of participating vehicles n that traverse a link during time interval t_i seconds follows a Poisson distribution with mean $\frac{Qpt_i}{3600}$. We also know that the traversal time experienced by a participating vehicle can be counted as a sample to the final estimate travel time value with probability p_s, which is determined by the flow rate in both directions. Thus the sample number X should also follow a Poisson distribution with mean $\frac{Qt_i pp_s}{3600}$.

An approximation for the unconditional variance of t_d is given by

$$Var[t_d] = \frac{\sigma^2}{E[x \mid x > 0]} = \frac{\sigma^2}{E[x]/P\{x > 0\}}$$
$$= \frac{\sigma^2}{Qt_i pp_s} \cdot \{1 - e^{-Qt_i pp_s})$$

(7.14)

Figure 7.4 and 7.5 show the effect of penetration rate on estimate accuracy under different variance of travel time. *COV* is the coefficient of variation and equals to σ_t / t_μ. To evaluate $P_r\{e_t < 0.1\}$, the probability that the average relative error in travel time is within 10%, we assume that the travel times of a segment are distributed normally. For same penetration rate and the same flow rate, varying *COV* from 15% to 25% decreases the performance from a confidence level of 97% to 83% (that the relative error in average travel time is within 10%). It is clear that performance increases with increasing flow rate, increasing penetration rate and decreasing the fleet travel time variability.

Figure 7.4 Effect of penetration rate on system performance (p = 5%)

Figure 7.5 Effect of penetration rate on system performance (Q = 700 veh/hr)

7.4 Discussion

The analytical statistical model presented in this chapter is a simple approach that allows us to evaluate the important parameters for a decentralized traffic information system and describe their interdependent. In addition, it allows us to predict the performance of the systems under a variety of traffic scenarios and conditions. The results are reasonable and consistent with the simulation results presented in the previous chapters. From Figure 7.4 and 7.5, we can see that when traffic flow is 700 vehicle /hour/link the probability that the average relative error in travel time is within 10% is greater than 90%, which is consistent with the simulation results shown in Chapter 6.

Chapter 8

Conclusions and Future Work

This chapter provides a summary of the dissertation, and some of the key conclusions and contributions. Further, future work is outlined, followed by a list of publications resulting from this research.

8.1 Conclusions and Contributions

This dissertation has presented a decentralized traffic information system design based on Inter-Vehicle Communication. The overall goal is of this research was to develop a scalable traffic information system with minimal or zero additional infrastructure. As IVC-equipped vehicles travel the roadways, they can share information on network traffic conditions and regional traffic information can be soon established. Decentralized systems avoid potential single point failures that a TMC-based system might have and are capable of covering roadways that do not have embedded loop detectors. The proposed system has successfully met this goal. The system's performance has been simulated for the Inland Empire Freeway Network in California. It can been seen from the simulation results that by using the proposed adaptive dissemination scheme together with a well-design estimation algorithm, a 5% IVC-equipped vehicle penetration rate can achieve more than 90% accuracy under typical conditions.

Key contributions from this work include:

- Several techniques on travel time estimation were extensively analyzed and evaluated. These techniques vary from simple blind averaging between all participating vehicles, to more sophisticated techniques using decay factors or filtered estimation. The simulation results show that both blind averaging and averaging with exponential smoothing have a serious problem that the earlier-generated estimate will dominate the final estimated value. However the results can be greatly improved if the travel time of a road segment is only estimated by the direct-experiencing vehicles

- An adaptive dissemination mechanism has been proposed and evaluated. Each participating vehicle can adapt their transmission interval according to the current traffic speed and also disseminate the traffic information of different segments at different rates according to the distance to its current position. It can be seem from the simulation results that the proposed mechanism is efficient to provide the reliable traffic information transmission for travel estimation.

- An analytical model was developed to examine the effect of the key parameters on the performance.

- An integrated traffic/communication environment has been implemented to simulate the effectiveness of this decentralized traffic information system. This environment can be used for a variety of other vehicle communication implementations.

8.2 Future Work

In the future, we plan to expand this research to consider more factors:

- A prototype of the system can be implemented and the real world experiments can be conducted to further demonstrate the feasibility and features of the decentralized traffic information systems.

- Many more key communication functions can be integrated into the simulation environment through a variety communication modules and APIs created for PARAMICS. With this functionality in place, the integrated simulation environment can be extended to other ITS application and used to evaluate the information propagation within the traffic network.

8.3 Publications Resulting from this Research

To date, this research has generated the following publications:

[1] Huaying Xu and Matthew Barth, "A Transmission-Interval and Power-Level Modulation Methodology for Optimizing Inter-Vehicle Communications", in *Proc. of the first ACM International Workshop on Vehicular Ad Hoc Networks*, Philadelphia, Pennsylvania, October, 2004.

[2] Huaying Xu and Matthew Barth, "Travel Time Estimation Techniques for Traffic Information Systems Based on Inter-Vehicle Communications", In *Proc. of the Transportation Research Board's 2003 Annual Meeting*, National Academies, Washington, D.C., January 2006.

[3] Huaying Xu and Matthew Barth, "Travel Time Estimation Techniques for Traffic Information Systems Based on Inter-Vehicle Communications", to appear, *Journal of the Transportation Research Board*, 2006.

[4] Huaying Xu and Matthew Barth, "An Adaptive Dissemination Mechanism for Inter-Vehicle Communication-Based Decentralized Traffic Information Systems", to appear, in *Procs of the 2006 IEEE Intelligent Transportation System Conference*, Toronto, Canada.

[5] Huaying Xu and Matthew Barth, "An Analytical Model of a Self-organizing Traffic Information System Using Inter-Vehicle Communication", in preparation, *IEEE Transactions on Intelligent Transportation Systems*

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