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An Adaptive Dissemination Mechanism for Inter-Vehicle Communication-Based Decentralized Traffic Information Systems

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Abstract—Inter-Vehicle Communications (IVC) has the potential to play an important role in many future vehicle and traffic applications. Much of this will occur in the automated vehicle control and safety systems (AVCSS) arena, and to a lesser extent in the Advanced Transportation Management and Information Systems (ATMIS) arena. One such ATMIS application where IVC can be used is in decentralized traffic information systems. These systems do not require extensive infrastructure and management centers to collect and disseminate traffic information. Instead, information can be shared among vehicles through periodic broadcast messages. An adaptive dissemination mechanism for this is described in this paper. 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 segments at different rates according to the distance to its current position. This dissemination scheme ensures the efficient distribution of information within the vehicle network. We have designed, developed, and tested this methodology using a unique traffic simulation environment that has been effectively augmented with wireless communication capability. Both analysis and simulation results show that the bandwidth that the system requires is far below the bandwidth of current 802.11 wireless links and the system can reach the accuracy requirement even at a low penetration rate.

Index Terms—Broadcast, Inter-vehicle communications, Decentralized traffic information system.

I. 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, 5, 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 [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, 9, 10, 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.

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. 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. To date, these two aspects of the system design have only been studied separately.

In this paper, an adaptive interval control broadcast scheme is proposed for an IVC-based decentralized traffic information system. 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. The remainder of this paper is organized as follows. Section 2 briefly surveys related work. Section 3 outlines the system structure, analyzes the bandwidth required for the system, and presents the proposed disseminate scheme. The simulation setup and results are described in Section 4. Section 5 concludes the paper and describes future work in this area.

II. RELATED WORK

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.

III. SYSTEM DESCRIPTION AND KEY ASSUMPTIONS

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. Each vehicle should: 1) have the capability of sensing its own state conditions (e.g., position, velocity, and link travel times); 2) be able to make estimates on traffic conditions; and 3) be capable of on-board inter-vehicle communication. A block diagram of the overall system structure is shown in Fig. 1. It is assumed that all participating vehicles have the same internal structure. In this solution, it is assumed that each participating vehicle is equipped with a GPS receiver, a digital network map consisting of network nodes and road segments (i.e., links), a dedicated short-range communication (DSRC) wireless interface, and a computing unit for traffic estimation algorithms. A simple database on-board is also included 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. Road segments or links are defined here as a stretch of a road between two successive exit points (junctions, intersections, etc). 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.

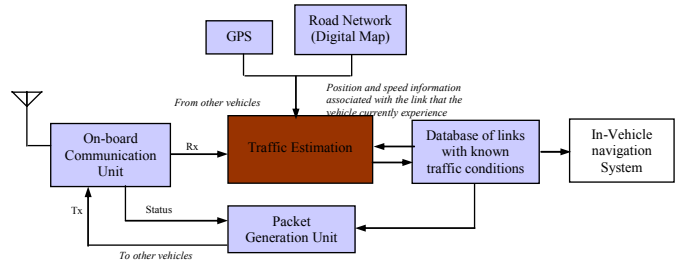


Fig. 1. Block diagram of a self-organizing traffic information system.

In the proposed system, travel time information for different road segments is disseminated among all participating vehicles using a single-hop broadcast scheme. 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 Section 4, 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.

IV. DISSEMINATION MECHANISM

A. 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 IEEE802.11 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 1000 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

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

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

$$v = v_f - v_f \cdot d / d_m$$

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 $2R/[k \cdot (v_1 + v_2)]$ 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:

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

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

$$n_{p_{\max}} = 2pkv_f d_m L$$

when $(d_1 + d_2) = d_m$.

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:

$$f(x; \Omega, m) = \left[2m^m x^{2m-1} / \Gamma(m)\Omega(m) \right] \exp(-mx^2/\Omega),$$

$$x \geq 0, \Omega > 0, m \geq 1/2$$

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

Table 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		

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]. 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]. The theoretical cross-over distance is given by $d_c = 4\pi h_t h_r / \lambda$, where h_t and h_r are transmitter and receiver antennae heights respectively and λ is the signal wavelength.

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 1. The m value is set to 0.75.

2) Required Bandwidth:

As illustrated in Fig. 2, 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 93% 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:

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

The maximum number of packets is given as $n_p'_{\max} = \left[\int_0^{\infty} P(x) dx / R \right] pkv_f d_m \cdot L$, 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 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 :

$$\begin{aligned} n_p'' &= 2 \int_0^{\infty} [n_v LP(x)/T] dx \\ &= 2 \int_0^{\infty} [(d_1 + d_2) pk(v_1 + v_2)L \cdot P(x)/2R] dx \\ &= 2 \int_0^{\infty} P(x) dx \cdot (d_1 + d_2) pL/T \end{aligned}$$

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.

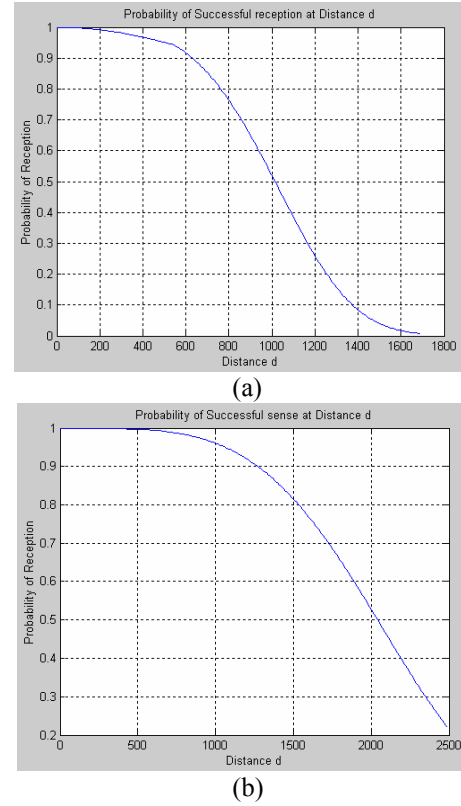


Fig. 2. Probability of (a) reception and (b) sensing at distance d when no interference is present.

B. Adaptive Interval Control Broadcast for Traffic Information Distribution

In [20] 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 [20], 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 $2R/[k \cdot (v_1 + v_2)]$.

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 $2R/[k \cdot (v_1 + v_2)]$, 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 $2R/[k \cdot (v_1 + v_2)]$, 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 $v(i) = t(i)/l(i)$ where $l(i)$ is the length of the segment in the network database. Fig. 3 shows the pseudo-code for this dissemination scheme.

```

Function Dissemination()
{
   $S_0$ : the road segment that the vehicle is traveling
   $S_1$ : the adjacent road segments
   $t_{i1}$ : the transmission interval to transmit traffic information of road segments  $S_1$ 
   $t_1$ : the time elapsed since last transmission for traffic information of road segments  $S_1$ 
   $S_2$ : the other road segments
   $t_{i2}$ : the transmission interval to transmit traffic information of road segments  $S_2$ 
   $t_2$ : the time elapsed since last transmission for traffic information of road segments  $S_2$ 
   $e_e$ : The event that the vehicle exits the road segment  $S$ 

  if ( $e_e$ )
    transmit_information( $S_0$ )
  end

  if ( $t_1 == t_{i1}$ )
    transmit_information( $S_1$ )
  end

  if ( $t_2 == t_{i2}$ )
    transmit_information( $S_2$ )
  end
}

```

Fig. 3: Pseudo-code for proposed dissemination scheme.

V. SIMULATION SETUP AND RESULTS

A. Integrated Simulation Environment

In order to simulate the effectiveness of this decentralized traffic information system, a sophisticated traffic simulator has been coupled with a powerful network communications model. The traffic simulator used is PARAMICS [21], which 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. In order to explore vehicle-based wireless communication techniques, we have 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 Fig. 4. Through its API, we extended the PARAMICS features to simulate the functionality of each component in the system structure (details of the simulation environment are the subject of an upcoming paper).

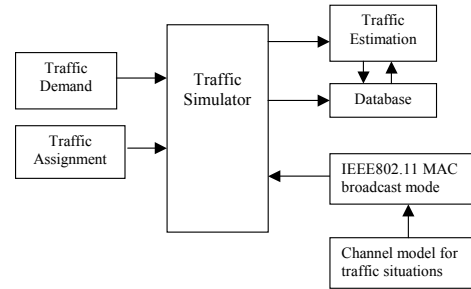


Fig. 4. Diagram of integrated simulation environment

B. 802.11a MAC Broadcast Mode

Communications are simulated between IVC-equipped vehicles using the IEEE802.11a broadcast mode. 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 chosen 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 1.

C. Scenarios and Results

In this study, two different scenarios are considered. First, a simple highway network is examined with different flow rates. Second, a real highway network is considered with realistic traffic flow calibrated from a travel demand model.

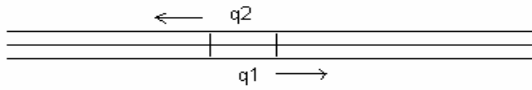


Fig. 5. First scenario: Ideal highway conditions.

The topology of the first scenario is a straight highway as shown in Fig. 5. 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, see Table 2). 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.

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. Fig. 6 shows this sample rate measure under different traffic flow conditions. The results of Fig. 6(a) are obtained when all traffic information is transmitted at the same constant rate $2R/[k \cdot (v_1 + v_2)]$. In contrast, Fig. 6(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.

To evaluate the effectiveness of the dissemination scheme across a larger, real-world network with calibrated travel demand, Southern California's Inland Empire freeway network was used as shown in Fig. 7. This network includes the I-10, I-15, CA-60, CA-91 and I-215 freeways, consisting of approximately 500 roadway links. In the simulation runs, origin-destination travel demand values are calibrated from the region's travel demand model, specified for a typical morning peak period from 7AM to 8AM. In the simulation, the traffic estimation technique from [20] is used in combination with the dissemination scheme described in this paper.

Table 2. Level of Service for Basic Freeway Section

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

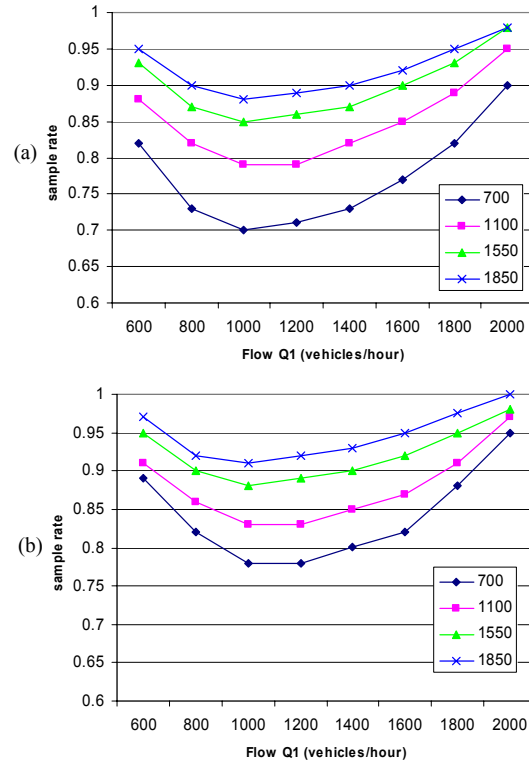


Fig. 6. Sample rate measure (ratio of the number of travel time samples that contribute to the average estimate travel time to the total number of participating vehicles that pass the studied link) under different traffic flow conditions for two scenarios. (a) without local frequent transmission; b) with local frequent transmission.

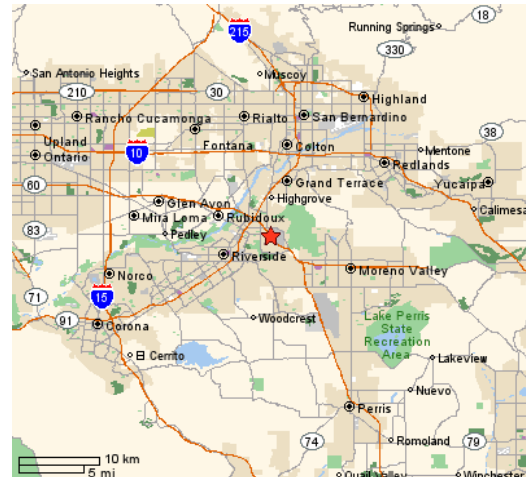


Fig. 7. Studied traffic network – Inland Empire Freeway Network

In the decentralized traffic information system, the travel time information of the different roadway links is distributed among vehicles as the simulation takes place. At any specified time, the travel time estimate of a link for a specific period in all vehicles' database can be viewed as a random variable that varies with time and space. To indicate the accuracy of the estimate value in all vehicles' database, we define the mean absolute percent error (MAPE) to represent the error between the estimate and ground truth as reported by the simulation. It can be expressed as the average absolute

percentage difference between the estimate and ground truth:

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

where n = the total number of vehicles whose database include the travel time estimate of road segment i ; $\hat{t}_{k,(t_1,t_2)}(i)$ = the travel time estimate of road segment i during the interval (t_1, t_2) in k th vehicle's database; and $t_{g,(t_1,t_2)}(i)$ = the ground truth of travel time for road segment i during the interval (t_1, t_2) .

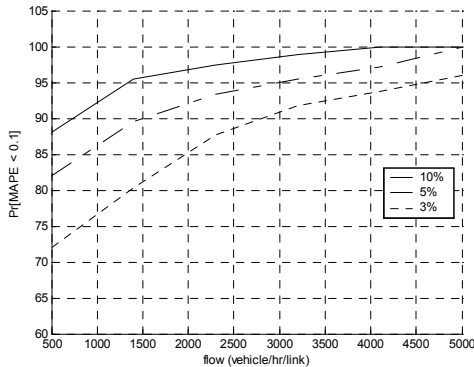


Fig. 8. Accuracy of travel time estimate versus traffic flow with different penetration rates.

We use the probability that MAPE in travel time is within 10%, $P_r\{MAPE < 0.1\}$, to evaluate the accuracy of the system. Fig. 8 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 Fig. 8), 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.

VI. CONCLUSIONS AND FUTURE WORK

In this paper, an adaptive transmission interval control broadcast scheme is presented for decentralized traffic information systems. 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 links at different rates according to the distance to its current position. Fig. 2 presents the transmission range and sensing range of typical DSRC wireless interface under traffic scenarios. Based on these transmission and sensing ranges, the analytical result shows that the bandwidth that the system requires is far below the bandwidth of current 802.11 wireless systems. This dissemination scheme ensures the distribution of the information that is necessary for travel time estimation in a

decentralized traffic information system. From the simulation results, it can see that by using this 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.

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