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A Load Balancing and Congestion-Avoidance Routing Mechanism for Teal-Time Traffic over Vehicular Networks

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Abstract: With the growth up of internet in mobile commerce, researchers have reproduced various mobile applications that vary from entertainment and commercial services to diagnostic and safety tools. Resource management for real-time traffic has widely been recognized as one of the most challenging problems for seamless access to vehicular networks. In this paper, a novel load balancing and congestion-avoidance routing mechanism over short communication range is proposed to satisfy the stringent QoS requirement of real-time traffic in vehicular ad hoc networks. Fuzzy logic systems are used to select the intermediate nodes on the routing path via inter-vehicle communications, and H-infinity technique is used to adjust the membership functions employed in the fuzzy logic systems to adapt to the volatile characteristics of the vehicular networks. Notably, a prediction of the remaining connection time among each vehicle and its neighbors is derived to assisting in the determination of the intermediate nodes on the routing path. The experimental results verify the effectiveness and feasibility of the proposed schemes, in terms of several performance metrics such as packet delivery ratio, end-to-end delay, control overhead, throughputs, call blocking probability and call dropping probability.

Keywords: vehicular ad hoc network (VANET), fuzzy logic, routing enhancement, H-infinity
Categories: C.2, C.2.2

1 Introduction

In recent years, the research on the intelligent transportation systems (ITSs) has been progressing intensively. ITS is a broad range of diverse technologies applied to make the roads safer, more efficient, more reliable, and less damaging to the environment, without having to physically alter existing infrastructure. The range of technologies involved includes the advanced information technologies, sensor technology, automatic control theory, operations research, artificial intelligence and cross-disciplines such as transportation, engineering, finance, electronic commerce and automobile manufacturing. The key in ITS is the interface between the driver/the traveler, the vehicle, and the roadway that can work as a single integrated environment through advanced communications, allowing for better management and use of the available transportation resources. One major problem in ITS is the analysis and management of traffic information. Although some information can be obtained easily though traditional query operation from traffic database, more important information containing characteristics of vehicular environment and forecast data needs to be extracted from the traffic database for further analysis and processing.

The transmission technology for ITS can be typically classified into two categories, i.e., road-to-vehicle communications (RVC) and inter-vehicle communications (IVC). The most important requirement for both RVC and IVC is the quality of service, especially the communication delay between end-to-end and the minimum consumption of network resources. Wireless mobile ad hoc network (MANET) technologies promise delivery of network access area without the need of infrastructure. However, MANET technologies can not be directly applied to IVCs since the characteristic of vehicle movement and relative speed of mobile nodes are different. There have been several researches [Mesh Networks Inc.][Cherry, 03] addressed on the construction of Ad hoc network among vehicles in the early stage of development of MANETs. Recently, the usage of MANETs as a base technology in IVCs has gained more popularity due to its potential applications, such as providing support for ITS and expediting Internet access in high ways.

Based on the IEEE 802.11p [Zhu, 03][National Highway Traffic Safety Administration, 00] standard for wireless access in vehicular environments, the recent introduction of dedicated-short-range communication (DSRC) devices has evoked considerable interest within the research communities and automotive industries. DSRC is designed to support high-speed, short-range, low-latency wireless communications for IVC and RVC. The 802.11p amendment can be viewed as an enhancement of 802.11a in which node association has significantly been simplified to enable rapid connection establishment and network acquisition.

It is well known that the major challenge for designing routing protocols in MANETs is to find a path from the source to the destination without any preconfigured information or regularly varying link situations. The position based routing becomes a suitable candidate for vehicular ad hoc networks (VANET) because this kind of routing protocol depends only on geographic position information and the information can be easily obtained by navigation systems, such as global position system (GPS) [Maihofer, 04][Imielinski, 96]. In addition, the dissemination of the network and road information can be more efficient if the base station allocated for RVCs can be arranged to participate in the determination of management policy or routing path construction in IVCs and RVCs.

Research work on RVCs can be roughly divided into three categories in literature, including unicast, flooding, and diffusion. Traditional ad hoc network routing protocols [Füssler, 02] or position based routing protocols [Mauve, 01][Wu, 04] can be used to establish general unicast communication in a VANET. A service discovery mechanism is then established to allow each node to obtain the needed information [Festag, 04][Morris, 00]. Nevertheless, the overhead such as the latency and diminished network capacity caused by the service discovery mechanism and routing table maintenance makes this method infeasible for most safety critical applications.

It is observed that the importance of sensed information about a particular location decreases with the distance to that location. Data is thus required to be disseminated in the vicinity of its origin. This is the case for most safety applications, but not for e.g. infotainment [Bogenberger, 03] or environmental applications, where all data comes from some remote site(s). Most IVC Protocols currently employ flooding to broadcast data. Their performance drops quickly as the number of nodes increases because each node receives and broadcasts the message simultaneously such that contentions, collisions, broadcast storms and high bandwidth consumption might occur [Ni, 99]. A so-called dedicated omni-purpose inter-vehicle communication linkage protocol for highway automation (DOLPHIN) [Tokuda, 00] is an example of IVC in this category. Selective flooding is used to disseminate the information in the reverse direction of vehicle movement. The nodes broadcasting the information are reselected in every communication hop and poor performance might occur for point-to-point communications. The GPS-based Message Broadcasting [Sun, 00] uses a better broadcasting system, similar to the single cast routing protocol, Zone Routing Protocol (ZRP). It performs much better than flooding based ones, but it still has routing overhead as long as the forwarding nodes are selected in every hop and is not efficient for point-to-point communications.

In [Korkmaz, 06], Korkmaz *et. al.* proposed a cross layer protocol by using clustering transmission (CVIA). They create single-hop vehicle clusters and mitigate the hidden node problem by dividing road into segments and controlling the active time of each segment. However, the assumption of each vehicle on the road moves at a fixed speed without considering the impact of mobility causes this approach infeasible in the application of VANETs. A coordinated external peer-communication (CEPEC) is a protocol permitting multiple accesses to the shared channels in one-hop scope and data relaying and routing in multi-hop scope [Yang, 07]. The advantage of CEPEC is to increase the end-to-end throughput while ensuring fairness guarantee in bandwidth usage among road sections.

Unlike all of the solutions mentioned above, this work exploits roadside base station assisted routing mechanism in order to adapt to the architecture of IVC/RVC and the specific characteristic of VANETs. Meanwhile, a load-balancing and congestion-avoidance routing protocol suiting for short-range communications is proposed to be employed by the vehicles located in the areas uncovered by the roadside base stations. Fuzzy logic systems are used to select the intermediate nodes on the routing path, and H-infinity technique is used to adjust the membership functions employed in the fuzzy logic systems to adapt to the volatile characteristics of the VANET. Notably, the remaining connection time among each vehicle and its neighbors is derived to assisting in the determination of the intermediate nodes on the routing path. A series of experiments were conducted to compare the proposed scheme with the representative vehicular ad hoc routing protocols in the literature, including CVIA and a recently presented state-of-the-art protocol, CEPEC. The experimental results showed that the proposed work achieves better performance than the two representative schemes in the literatures in terms of several performance metrics such as packet delivery ratio, end-to-end delay, control overhead, throughputs, call blocking probability and call dropping probability.

The remainder of this paper is organized as follows. Section 2 presents the load balancing and congestion-avoidance routing mechanism. The simulation results are given in Section 3. Conclusion is made in Section 4.

2 Load balancing and congestion-avoidance routing mechanism

In this work, the robust communications in the VANETs are established by constructing a load balancing and congestion-avoidance routing path for packets transmitted through IVC or RVC. The IVC/RVC protocol adopted in this work is similar to the approach taken in the AODV. That is, an acknowledgment (ACK) packet is sent back to the source node when the destination node receives a packet in order to certify that each packet is successfully delivered. Notably, the reason for selecting AODV-like protocol in this work is that the route discovery mechanism in a connection-oriented protocol, such as AODV, precisely matches the bandwidth calculation scheme and is suitable for bandwidth constrained routing. In addition, AODV provides some minimal control to enable nodes to specify Quality of Service (QoS) parameters, namely maximal delay or minimal bandwidth.

The packet traffic is classified as either real-time or non real-time traffic in this work. Figure 1 depicts the routing path determination process for real-time traffic in vehicular networks. When a vehicle submits a real-time transmission request, the vehicle will first attempt to connect directly with the base station within its transmission range. The base station permits the connection request if the required bandwidth of the real-time request is less than or equal to the bandwidth provided by the base station. The allocable bandwidth at the base station is defined by,

$$Bw_a = Bw_{unused} + \sum_i \left(Bw_{i,non-rt} - Bw_{i,min}\right) - Bw_e - \sum_j Bw_{j,rt}\ , \tag{1}$$

where Bw_{unused} denotes the unused bandwidth at the base station, $Bw_{i,non\text{-}rt}$ represents the bandwidth currently allocated for the non-real-time traffic with index i, $Bw_{i,min}$ stands for the minimum bandwidth required for the non real-time traffic with index i, Bw_e is the bandwidth reserved for transmission of emergency events, and $Bw_{j,rt}$ is the bandwidth currently allocated for the real-time traffic with index i.

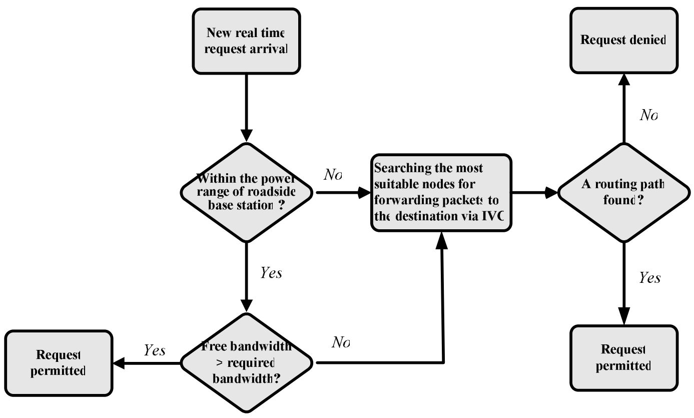

Figure 1: Routing path determination process for real-time traffic in vehicular networks.

In case no base station can be found or QoS requirement of its request can not be satisfied by the closest base station, the vehicle will attempt to find a route along the way to the destination via the IVC. The source vehicle first broadcasts a packet to find a route to the destination. Each vehicle on the way to the destination is asked to reply to the source vehicle whether it is appropriate for forwarding the real-time packets to the destination. The appropriateness of each intermediate node along the way to the destination is determined by a fuzzy logic inference system installed at each vehicle. After the broadcast packet reaches either the destination itself or the closest base station on the route to the destination, a routing path is then constructed by selecting the most appropriate node to forward the packets at each road segment along the way to the destination or the closest base station. Fig. 2 shows an example of the routing process. Here the radius of the coverage area of each vehicle is assumed to be identical to the length of a road segment. The request is denied if there exist any road segments at which no intermediate node can be arranged to forward the packets.

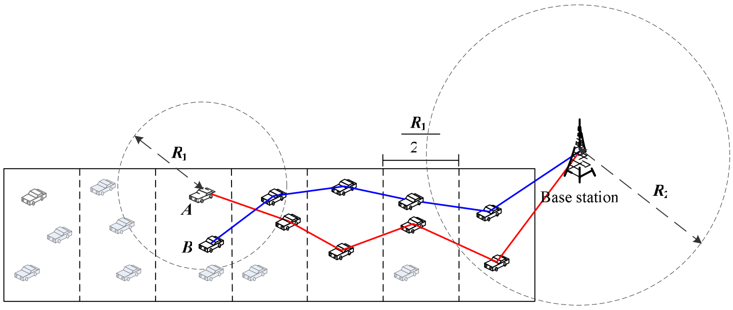

Figure 2: An example of short range communications through IVC.

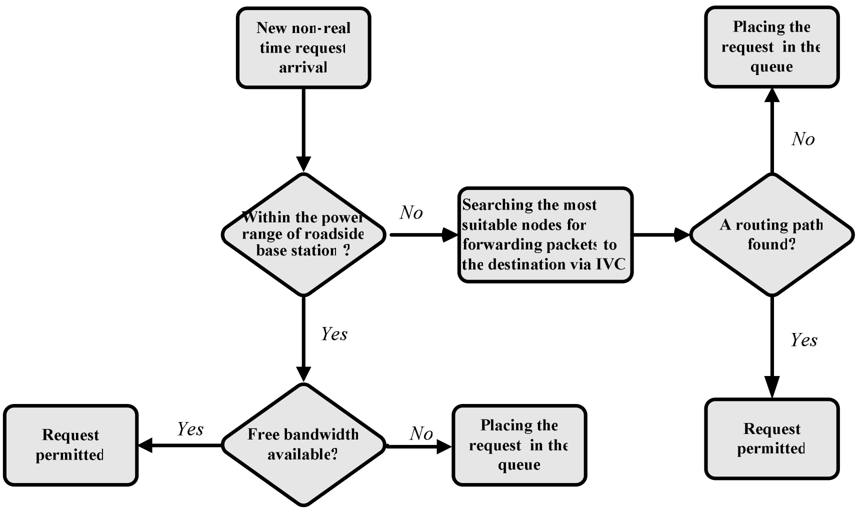

Figure 3: Routing process for non-real-time traffic in vehicular networks.

Figure 3 illustrates the routing path determination process for non-real-time traffic in vehicular networks. When a vehicle submits a non-real-time transmission request, the vehicle will first attempt to connect directly with the base station within its transmission range. The non-real-time request is allowed to connect with the base station as long as there is any free bandwidth at the base station. In case no base station can be found, the vehicle will attempt to find a route along the way to the destination via the IVC. The source vehicle first broadcasts a packet to find a route to the destination. Each vehicle on the way to the destination is asked to reply to the source vehicle whether it is appropriate for forwarding the non-real-time packets to the destination. The appropriateness of each intermediate node along the way to the destination is again determined by the fuzzy logic inference system installed at each vehicle. After the broadcast packet reaches either the destination itself or the closest base station on the route to the destination, a routing path is then constructed by selecting the most appropriate node to forward the packets at each road segment along the way to the destination or the closest base station. If no routing path can be found, the non-real-time request will be placed in the queue at the source vehicle until a preset time-out is reached.

2.1 Determination of routing path by using fuzzy logic inference system

As mentioned in the preceding paragraph, the construction of the routing path via IVC can be obtained by selecting the most appropriate intermediate node at each road segment along the way to the destination, assuming the radius of the coverage area of each vehicle is identical to the length of a road segment. The determination of the most appropriate intermediate node at each road segment is fulfilled by comparing the feedback values sent back by the vehicles distributed at the road segment,

$$inode = \max_i \quad \mathrm{fl}_i(\cdot), \tag{2}$$

where $\mathrm{fl}_i(\cdot)$ represents the output generated by the fuzzy logic inference system established at the vehicle indexed by *i*. Notably, the fuzzy logic systems are employed to determine the intermediate nodes for the short range communication in IVC owing to their effectiveness in solving several resource assignment problems efficiently in wireless networks in the literature [Hirota, 93]. The basic functions of the four main components are described as follows:

- **Fuzzifier**: The fuzzifier performs the fuzzification function to convert three inputs into suitable linguistic values needed in the inference engine.
- **Fuzzy rule base**: The fuzzy rule base is composed of a set of linguistic control rules and the attendant control goals.
- **Inference engine**: The inference engine simulates human decision-making based on the fuzzy control rules and the related input linguistic parameters.
- **Defuzzifier**: The defuzzifier acquires the aggregated linguistic values from the inferred fuzzy control action and generates a non-fuzzy control output.

The input-output mapping for the fuzzy logic inference system established at the vehicle indexed by *i* can be expressed by,

$$A_{rt,i} = \mathrm{fl}_i(R, L, B), \tag{3}$$

where the input *R* denotes the minimum bandwidth required for satisfying the real-time traffic, *L* is the expected remaining connection time between the vehicle indexed by *i* and its neighbor vehicles, and *B* is the bandwidth currently used at the vehicle indexed by *i*. Notably, the expected remaining connection time between the vehicle indexed by *i* and its neighbor vehicles represents the expected remaining time that the neighbor vehicles stay within radio range of the vehicle indexed by *i* during the next time period. The algorithm of computing the expected remaining time will be given in the subsequent section.

Figure 4 illustrates the reasoning procedure of the fuzzy logic systems. μ denotes the degree of membership. The three inputs *R*, *L*, and *B* are the same as the ones specified in Eq. (3). The fuzzy linguistic variables "Small", "Middle" and "High" give different required minimum bandwidth measures in the membership function for the input *R*. Similarly, three linguistic term sets, "Slow", "Medium" and "Fast" are used for *L*, and "Small", "Middle" and "High" are used for *B.* The output parameter of the inference engine, $A_{rt,i}$, the appropriateness of the vehicle as an intermediate node of the link, is defined as the estimated link quality when the vehicle is chosen as the intermediate node. The range of the output falls between 0 and 1.

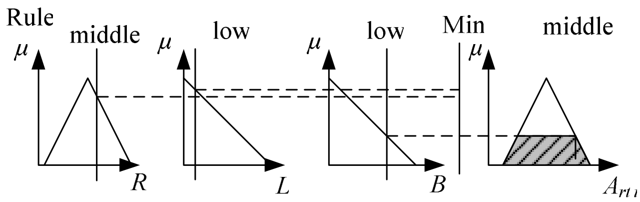

Figure 4: The reasoning procedure for Tsukamoto defuzzification method.

The non-fuzzy output of the defuzzifier can then be expressed as the weighted average of each rule's output after the Tsukamoto defuzzification method is applied:

$$A_{rt,i} = \frac{\sum_{j=1}^{27} A_{rt,i,j} \cdot w_j}{\sum_{j=1}^{27} w_j}, \tag{4}$$

where $A_{rt,i,j}$ denotes the output of the *j*th rule induced by the firing strength w_j.

We also select the intermediate nodes of the routing path for non-real-time traffic by using fuzzy logic systems. The input-output mapping for the fuzzy logic system used for non-real-time traffic is expressed by,

$$A_{non-rt,i} = \mathrm{fl}_i(Q, L, B), \tag{5}$$

where *Q* denotes the length of the queue for the non-real-time traffic placed at the vehicle indexed by *i*. *L* is the expected remaining connection time between the vehicle indexed by *i* and its neighbor vehicles, and *B* is the bandwidth currently used at the vehicle indexed by *i*. The queue length, *Q*, is defined as the number of packets currently buffered in the interface queue of the vehicle indexed by *i* [Balakrishnan, 07]. When a vehicle does not have enough buffers to accommodate data packets originated from the new route, it is easy for the new route to cause congestion.

Once the most appropriate intermediate node at each road segment along the way to the destination is selected by using fuzzy logic inference systems, the routing path for the real-time/non-real-time traffic can be determined accordingly. Notably, the consideration of the congestion situation at each vehicle is implicitly addressed in the input parameters to the fuzzy logic systems. It can be expected that the functionality of load-balancing and congestion avoidance is automatically provided in the proposed routing mechanism.

2.2 Tuning of parameters of the membership functions by using H-infinity filtering

Given a rule base, the membership functions can be trained to enhance the performance of the above-mentioned fuzzy logic systems. To speed up the learning process, the fuzzy logic inference systems employ the predefined membership functions based on experience as the initial premise membership functions in order to avoid starting tuning procedure from scratch. The training data is obtained by collecting the data from the system when the performance metric, packet delivery ratio, is higher than some predefined threshold for several consecutive time intervals. In addition, the learning process will be reactivated whenever the packet delivery ratio drops below a preset threshold for several consecutive time intervals in order to adapt to the volatile VANET environment.

In this work, the H-infinity filter [Willmann, 07][Simon, 02] is used to train the membership functions of the fuzzy logic systems. The motivation of using the H-infinity filter here is that the H-infinity filter is shown to be more robust to system noise, modeling errors, and nonlinearities than other representative methods in the literature, such as the Kalman filter [Trees, 1968][Simon, 06].

We assume that the derivative of an *m*-element vector *a* with respect to a *p*-element vector *b* is,

$$\frac{\partial a}{\partial b} = \begin{bmatrix} \frac{\partial a}{\partial b} & \cdots & \frac{\partial a}{\partial b} \\ \vdots & & \vdots \\ \frac{\partial a}{\partial b} & \cdots & \frac{\partial a}{\partial b} \end{bmatrix}, \quad (6)$$

Consider a nonlinear time-invariant finite dimensional discrete time system of the form,

$$x_{n+1} = f(x_n) + Bw_n + \delta_n, \quad (7)$$

$$d_n = h(x_n) + v_n, \quad (8)$$

where the vector x_n is the state of the system at time *n*, w_n and v_n are white noise, δ_n is an arbitrary noise sequence, d_n is the observation vector, and $f(\cdot)$ and $h(\cdot)$ are nonlinear vector functions of the state.

The problem addressed by the H-infinity filtering is to find an estimate $\bar{x}_{n+1}$ of x_{n+1} given $\{d_0,...,d_n\}$ such that the infinity norm of the transfer function from the augmented noise vector to the estimation error is bounded by a user-defined quantity γ,

$$\|G_{ye}\|_\infty < \gamma, \quad (9)$$

where the augmented noise vector e_n and the estimation error y_n are defined as follows,

$$e_n = \left[w_n^T \;\; v_n^T \right]^T , \tag{10}$$

$$y_n = x_n - \bar{x}_n . \tag{11}$$

It can be shown [Willmann, 07] that the desired estimate can be obtained by the following recursive H-infinity estimator,

$$F_n = \left. \frac{\partial f(x)}{\partial x} \right|_{x=\bar{x}_n} , \tag{12}$$

$$H_n = \left. \frac{\partial h(x)}{\partial x} \right|_{x=\bar{x}_n} , \tag{13}$$

$$Q_0 = E(x_0 x_0^T) , \tag{14}$$

$$Q_n (I - H^T H P_n) = I - \frac{Q_n}{\gamma^2} P_n , \tag{15}$$

$$Q_{n+1} = F P_n F^T + B B^T , \tag{16}$$

$$K_n = F P_n H^T , \tag{17}$$

$$\bar{x}_{n+1} = F \bar{x}_n + K (d_n - H \bar{x}_n) , \tag{18}$$

where $\{Q_n\}$ and $\{P_n\}$ are nonsingular sequences of matrices. K_n is known as the H-infinity gain. In the case of a linear system it can be shown that the covariance of the estimation error is bounded by Q [Willmann, 07].

$$E[(x_n - \bar{x}_n)(x_n - \bar{x}_n)^T] \le Q_n . \tag{19}$$

2.3 Computation of remaining connection time between each vehicle and its neighbors

As described in Section 2.1, the remaining connection time between each vehicle and its neighbor vehicles is adopted as one of the input parameters of the fuzzy logic systems. We first assume that each vehicle always keeps constant speed. The remaining connection time between each vehicle and its neighbors is estimated based on the information of the current speed and the position of all vehicles. We then consider the possibility of each vehicle's speed change and derived the probability that each vehicle will disconnect with its neighbor vehicles. The remaining connection time between each vehicle and its neighbors is accordingly rectified to reflect the real-life situations.

2.3.1 Primitive method for computing remaining connection time of each vehicle and its neighbor vehicles

It is first assumed that two vehicles move to the same direction. The remaining connection time between the vehicle indexed by a and its neighbor vehicle b can be expressed by,

$$T_1 = \frac{\sqrt{R^2 - w^2} + \alpha \sqrt{{E_{a,b}}^2 - w^2}}{| v_a - v_b |} , \tag{20}$$

where $\alpha = 1$ when $v_a - v_b > 0$, $\alpha = -1$ when $v_a - v_b < 0$, R denotes the radius of the coverage area of each vehicle, w represents the width of each lane, $E_{a,b}$ is Euclidean distance between two vehicles, and v_a stands for the current speed of the vehicle indexed by a.

We next consider that two vehicles move to the opposite direction. The remaining connection time between the vehicle indexed by a and its neighbor vehicle b can be obtained by,

$$T_1 = \frac{\sqrt{R^2 - w^2} + \alpha\sqrt{E_{a,b}{}^2 - w^2}}{v_a + v_b}, \quad (21)$$

where R denotes the radius of the coverage area of each vehicle, w represents the width of each lane, $E_{a,b}$ is Euclidean distance between two vehicles, and v_a is the current speed of the vehicle indexed by a. $\alpha = 1$ when the two vehicles move toward each other, and $\alpha = -1$ when they move away from each other.

2.3.2 Remaining connection time computation based on probability distribution

In the preceding subsection, the possibility of ongoing change of vehicle's speed is ignored in the calculation of remaining connection time computation. This is an impractical assumption because the vehicle's speed can vary from minute to minute. We thus amend Eqs. (20) and (21) by considering the effect of the vehicle's speed change,

$$T_2 = T_1 \times \mathrm{P}(a,b), \quad (22)$$

where T_1 denotes the remaining connection time computed by Eqs. (20) or (21), and $\mathrm{P}(a,b)$ represents the probability of vehicles a and b keep connected during next period of T_1. $P(a,b)$ can be further expressed by,

$$\mathrm{P}(a,b) = \max_{d_a, d_b}\{\Pr(d_a) \times \Pr(d_b)\}, \quad (23)$$

where $\Pr(d_a)$ and $\Pr(d_b)$ denote the probabilities that vehicles a and b move during next period of T_1, respectively. d_a and d_b represent the moving distances of vehicles a and b during next period of T_1, respectively. The relationship between d_a and d_b is depicted in Fig. 5. Here R denotes the radius of the coverage area of each vehicle.

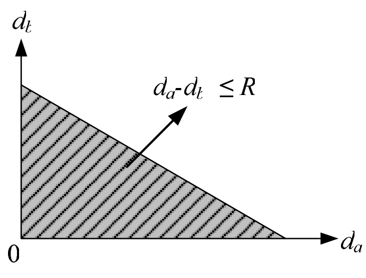

Figure 5: The relationship between d_a and d_b.

Eq. (23) can be further expanded by assuming the moving distance of each vehicle during next period of T_1 follows the log-normal distribution,

$$\Pr(y)=\begin{cases}\int_0^{d_y}\frac{1}{x\sigma_y\sqrt{2\pi}}e^{-\frac{(\ln(x)-\frac{v_y\times T_1}{2})^2}{2\sigma_y^2}}dx & ,\text{if } 0\le\alpha_y\le 1\\ \int_0^{d_y}\frac{1}{x\sigma_y\sqrt{2\pi}}e^{-\frac{[\ln(x)-\frac{v_y\times T_1}{2}(1+\frac{1}{\alpha_y})]^2}{2\sigma_y^2}}dx & ,\text{if } 1<\alpha_y\\ \int_0^{d_y}\frac{1}{x\sigma_y\sqrt{2\pi}}e^{-\frac{(\ln(x)-\frac{v_y\times T_1}{2})^2}{2\sigma_y^2}}dx & ,\text{if } -1\le\alpha_y\le 0\\ \int_0^{d_y}\frac{1}{x\sigma_y\sqrt{2\pi}}e^{-\frac{[\ln(x)-\frac{v_y\times T_1}{2}(1-\frac{1}{\alpha_y})]^2}{2\sigma_y^2}}dx & ,\text{if } \alpha_y<-1\end{cases}, \quad (24)$$

where d_y represents the moving distances of vehicle y during next period of T_1, v_y denotes the current speed of vehicle y, σ_y represents the variance of v_y, and α_y is the acceleration of vehicle y. Notably, the real mobility traces as reported in [Härri, 07] revealed that the speed and the pause times follow a log-normal distribution. We thus adopt the log-normal distribution for the moving distances of the vehicles in this work.

Figure 6 depicts the log-normal probability distributions for the moving distance of vehicle y when the vehicle speed is accelerated during next period of T_1, while Fig. 7 shows the log-normal probability distributions of vehicle y's moving distance when the vehicle decelerates its speed during next period of T_1. The notation P denotes the probability of vehicle y's moving distance. $d_{y,c}$ represents the moving distance of vehicle y when vehicle y keeps current speed during next period of T_1, and d_y stands for the moving distance of vehicle y after reflecting the speed change of vehicle y during next period of T_1. Whether a vehicle is within the communication range of its neighbors is accordingly determined by computing the distances of the vehicle and its neighbors during next period of T_1.

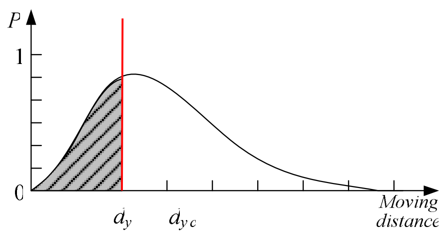

Figure 6: Log-normal probability distributions for the moving distance of vehicle y if y decelerates its speed during next period of T_1.

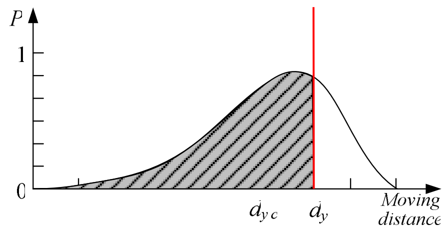

Figure 7: Log-normal probability distributions for the moving distance of vehicle y if y accelerates its speed during next period of T_1.

Based on Eqs. (23) and (24), the relationship between the relative distance of two vehicles, D, and the probability of two vehicles keeping connected during next period of T_1, P, is illustrated in Fig. 8. When the relative distance of two vehicles is smaller than the coverage range of each vehicle, R, the probability of two vehicles keep connected during next period of T_1, P, becomes higher, and vice versa.

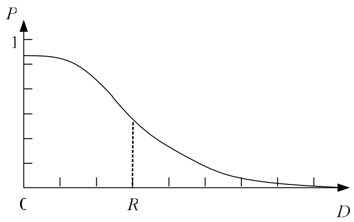

Figure 8: Relationship between the relative distance of two vehicles and the probability of two vehicles keep connected during next period of T_1.

3 Simulation results

We ran a series of simulations to evaluate the performance of the proposed work by using a network simulator written in C++. The results are averaged over 130 runs with a randomly generated topology in each run. The total simulation time for each run is 500 seconds. The compared schemes include the proposed load balancing and congestion-avoidance routing mechanism using traditional fuzzy logic systems (FL), the proposed fuzzy routing mechanism trained with H-infinity filtering (FLHF), and two representative cross layer routing protocol for vehicular networks in the literature, CVIA [Korkmaz, 06] and CEPEC [Yang, 07].

3.1 Simulation scenario

The highway simulation environment setup was replicated from [Yang, 07]. We initially randomly deployed vehicles. 5000-m-long straight stretch of highway with four lanes was constructed as the high speed moving environment. 50 vehicles were randomly distributed on the highway. Each vehicle was randomly placed in a lane. The initial velocity assigned to each vehicle was the average speed of the lane which they were placed in. In order to simulate the road traffic, the traffic flow is simulated with microscopic model [van Arem, 06]. Developed by the Federal Highway Authority, microscopic vehicle traffic simulator is able to provide vehicle traffic simulation data that are very close to real traffic data. The detailed simulation parameters are listed in Table 1.

Notably, CBR/UDP traffic is generated between randomly selected pairs of vehicles and the bandwidth of the base station is 54Mbps. There are two service classes, including real-time and non-real-time traffics. The CBR data packet size is 512 byte and packet rate is 4 packets per second. Each vehicle moves along the direction of the pathway, and the speed is randomly changed within a preset range during a fixed period of time.

Parameter type	Parameter value
Simulation time	500 sec
Length of highway	5000 m
Length of the road segment	500 m
Average traffic density	20 ~ 80 veh/km
Traffic model	Microscopic model
Maximum vehicle speed	50m/s
Mac protocol	802.11p (DSRC)
Maximum transmission range	1000 m
Bandwidth of base station	6M - 24M bps
Class of traffic	real-time, non-real-time
CBR real-time data sessions	25

Table 1: Simulation parameters.

3.2 Simulation results and analysis

The performance metrics given in this work include packet delivery ratio, end-to-end delay, control overhead, throughputs, call blocking probability and call dropping probability. The packet delivery ratio is the total amount of received packets divided by the total amount of packets transmitted during the simulation. The end-to-end delay is the average time elapsed for delivering a packet from the transmitter to the receiver. The control packet overhead is the ratio from the total transmitted control packets to the total received packets. Throughput is the total kilobits per second received by the destination. Call blocking probability and call dropping probability are probabilities that a new call request is denied for connection and a call experiences a premature call termination, respectively.

We first investigated the impact of traffic density on the network performance. The average traffic density is varied at 20, 35, 50, 65 and 80 veh/km. Next we examined how the network performance was affected by different speeds of the vehicles. Similar to [Taleb, 07][Taleb, 06], The speed of a vehicle between the vehicle's current location and its next destination is chosen from a uniform distribution between *avg* ± 10% kilometers per hour (km/hr). Here *avg* is set to 25, 50, 75, 100 and 125. For example, the speeds of all vehicles fall between 45 and 55 m/s when *avg* is set to 50 m/s.

Figure 9 shows the packet delivery ratio of the overall traffic for the four schemes under different moving speeds. The two proposed FLHF and FL mechanisms perform better than the other two because these two schemes can effectively construct load balancing routing paths to avoid the packets being dropped due to link congestion. Notably, the packet delivery ratio for FLHF and FL still keep at around 75% even the average traffic density is significantly increased in a high speed moving environment. In contrast, the CVIA scheme has the worst packet delivery ratio for overall traffic due to rapidly increased hop counts on the routing path. Figure 10 exhibits the throughputs of overall traffic for four schemes. FLHF outperforms FL, CVIA and CEPEC as expected due to lower packet delivery ratio.

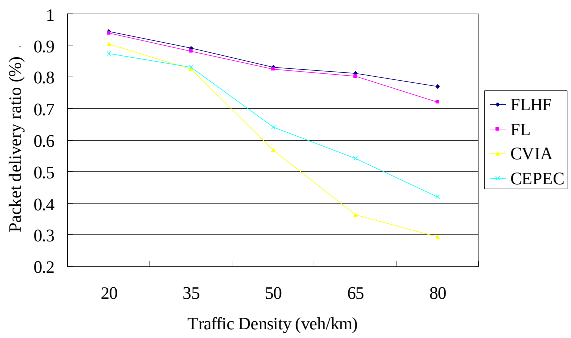

Figure 9: Packet delivery ratios of overall traffic for four schemes under different traffic densities.

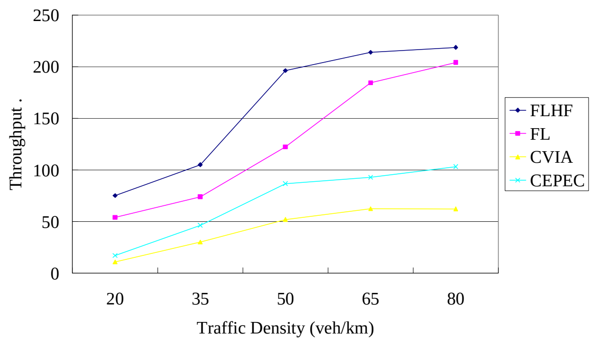

Figure 10: Throughputs of overall traffic for the four schemes under different traffic densities.

Figure 11 shows the control overhead for the four schemes under different traffic density. The control overhead is the required number of control packets needed for completing a packet transmission. Apparently, CVIA and CEPEC produce higher control overhead than the two proposed schemes. CVIA needs to generate control messages to maintain the transmission group periodically and CEPEC must issue control messages between a head vehicle and other vehicles in a segment such that a centralized-scheduling algorithm can be adopted within a segment.

The two proposed scheme maintain the routing path by means of piggybacking congestion-avoiding routing information in the packets and hence lower the control overhead.

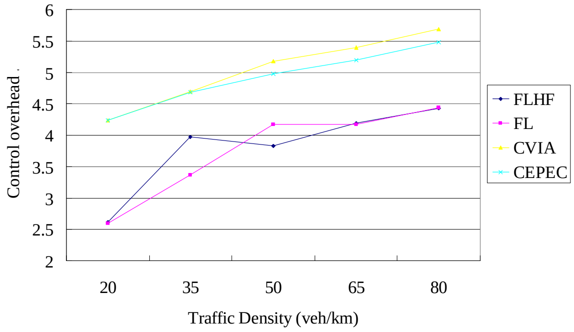

Figure 11: Control overhead of overall traffic for the four schemes under different traffic densities.

Figure 12 shows the comparison of call dropping probability (CDP) of real-time traffic. FLHF has the lowest CDP because FLHF can efficiently schedule different routes for real-time traffic. CVIA has the poorest performance as expected since it is not considerate of the QoS requirement of real-time traffic. FLHF outperforms FL owing to the application of H-infinity filtering in training the membership functions of the fuzzy logic systems in order to adapt to the volatile VANET environment.

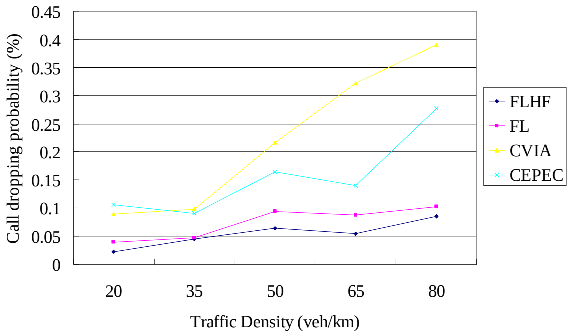

Figure 12: CDP of real-time traffic under different traffic densities.

Figure 13 illustrates the call blocking probability (CBP) for real-time traffic. The CBP for the new connections in the two proposed schemes is significantly better than the other two at higher traffic densities. The proposed fuzzy routing schemes effectively arrange the suitable routes for real-time requests under heavy traffic. The CVIA scheme has the highest CBP for real-time traffic because the packets are always transmitted through fixed routes and the congestion becomes more serious when the traffic is heavy. Figure 14 shows the throughputs of real-time traffic for four schemes. FLHF outperforms the other three as expected due to lower CDP and CBP.

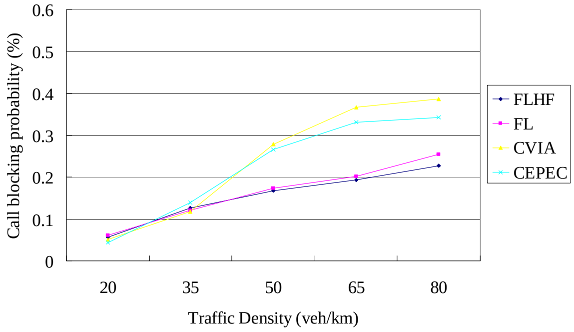

Figure 13: Call blocking probability (CBP) of real-time traffic under different traffic densities.

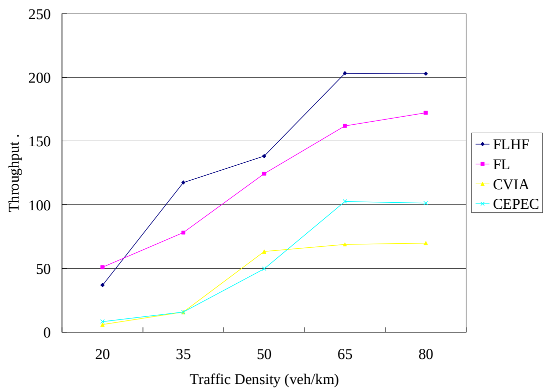

Figure 14: Throughputs of real-time traffic for the four schemes under different traffic densities.

Figure 15 shows the end-to-end delay of non-real-time traffic for the four schemes under different traffic densities. Notably, the end-to-end delay of non-real-time traffic in this work includes the routing delay plus other processing delays such as the computation of fuzzy logic algorithm. The delay is measured for those packets from the mobile source vehicle to the mobile destination vehicle. The two proposed schemes not only transmit packets through more suitable paths but also prevent packet loss from the events of link failure. On the contrary, CVIA scheme performs worse than two proposed schemes due to a significant increase of hop counts on the routing path. The increase of hop counts is caused by the quickly changed topology of the moving vehicles. The packets must go through more hops to reach the destination and this causes a longer transmission delay in CVIA scheme. Moreover, CEPEC scheme performs the worst among all schemes. Given a fixed amount of available bandwidth, the lengths of vehicle queues start to increase after reaching saturation status. Thus, the delay in CEPEC scheme starts to increase rapidly when the traffic density increases.

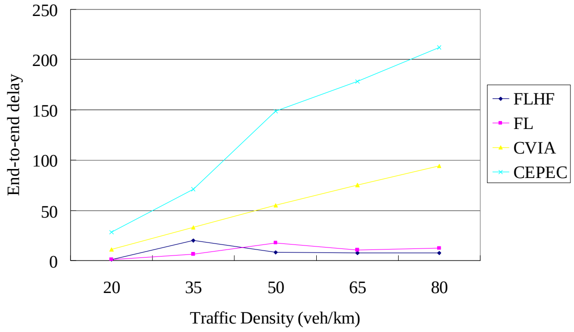

Figure 15: End-to-end delay of non-real-time traffic for the four schemes under different traffic densities.

Figure 16 and Figure 17 show the packet delivery ratio and the throughputs for four schemes under different speeds of the vehicles, respectively. As expected, the packet delivery ratio and throughputs deteriorate as the speeds of the vehicles are increased. Nevertheless, these two figures still exhibit the higher stability of FLHF. Figure 18 shows the control overhead when the speed of the vehicle is varied. FLHF introduces fewer broadcasts, and hence the control overhead is also reduced. Meanwhile, the control overhead significantly increases as the speed is increased for both CVIA and CEPEC.

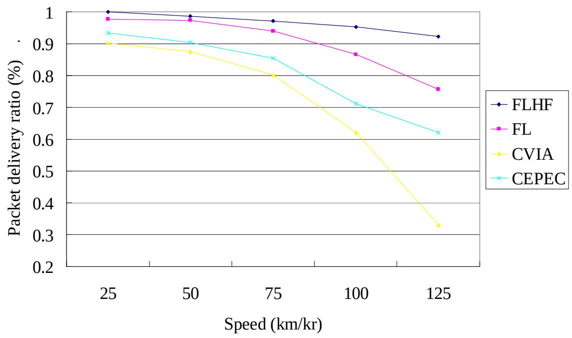

Figure 16: Packet delivery ratios of overall traffic for four schemes under different speeds of the vehicles.

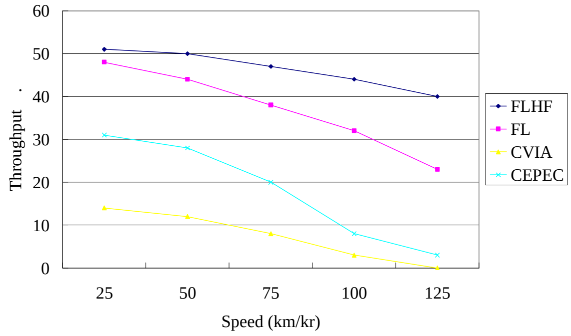

Figure 17: Throughputs of overall traffic for the four schemes under different speeds of the vehicles.

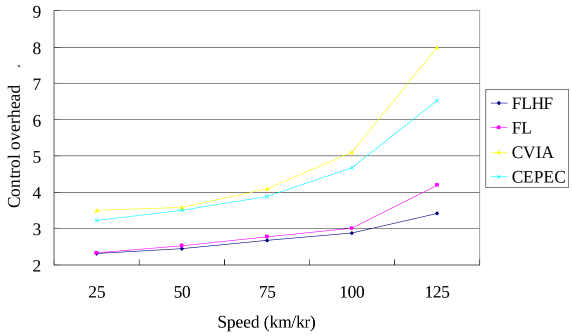

Figure 18: Control overhead of overall traffic for the four schemes under different speeds of the vehicles.

To illustrate the effectiveness of H-infinity filtering technique employed in this work, H-infinity filtering technique is compared with two other fuzzy well-known parameters adaptation methods, including neural networks and genetic algorithm. Table 2 gives the comparison of training time and execution time for the three algorithms during 130 runs of the simulations. It can be observed that the average accuracy rates for H-infinity filtering and neural networks are comparable, whereas the training time for neural networks and genetic algorithm are much longer than that of H-infinity filtering. Thus, neural networks and genetic algorithm are not suited for the real-time applications, especially for the VANET environment where frequent training is required due to the ongoing network topology changes.

	H-infinity Filtering	**Neural Networks**	**Genetic Algorithm**
Training time	102 µs	5806 µs	3045 µs
Execution time	52 µs	98 µs	2013 µs
Average accuracy rate	91.23 %	94.88 %	65.07 %

Table 2: Comparison of train time and execution time for the H-infinity filtering, neural networks and genetic algorithm algorithms.

An overall comparison of the experiment results for the four schemes is listed in Table 3. Generally speaking, the overall performance of the proposed FLHF and FL schemes are much better than the other two in terms of the metrics, including packet delivery ratio, end-to-end delay, control overhead, throughputs, call blocking probability and call dropping probability. The feasibility of the proposed schemes is thus verified.

4 Conclusions

In this paper, a novel load balancing and congestion-avoidance routing mechanism over short communication range is proposed to satisfy the stringent QoS requirement of real-time traffic in vehicular ad hoc networks. Fuzzy logic systems are used to select the intermediate nodes on the routing path via inter-vehicle communications. H-infinity technique is adopted to dynamically tune the membership functions employed in the fuzzy systems to adapt to the volatile characteristics of VANETs. Notably, a prediction of the remaining connection time among each vehicle and its neighbors is derived to assisting in the determination of the intermediate nodes on the routing path. The experimental results revealed the proposed load-balancing route construction mechanisms can achieve excellent performance in highway traffic scenario in terms of metrics, including packet delivery ratio, end-to-end delay, control overhead, throughputs, call blocking probability and call dropping probability, owing to the effective prevention of the link breaks and congestion occurrences caused by varied vehicle movements and traffic flows. The feasibility of the proposed schemes is thus verified. In the future work, we will investigate whether the proposed schemes should be amended to fit for the distinct characteristics of city traffic scenario. Meanwhile, multipath transmission techniques and heterogeneous wireless access technologies, such as WiMAX and 2G/3G, will be considered to provide a scalable framework for delivering real-time and best effort services over heterogeneous vehicular networks and ensure interoperability, roaming, and end-to-end session management.

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Traffic density (veh/km)	20	35	50	65	80
Packet delivery ratio (%)					
FLHF	94.6%	89.8%	83.9%	81.9%	76.5%
FL	93.5%	88.7%	82.8%	78.81%	70.6%
CVIA	91.2%	82.3%	56%	36.2%	29.3%
CEPEC	87.4%	83%	64.1%	54%	41.4%
Throughputs of overall traffic (kbps)					
FLHF	75	105	196	214	218
FL	54	73	122	184	188
CVIA	10	29	51	62	62
CEPEC	17	46	86	92	103
Throughputs of real-time traffic (kbps)					
FLHF	37.03	117.53	138.23	203.3	202.923
FL	50.88	78.11	124.38	161.84	172.3
CVIA	5.92	15.69	63.26	68.88	69.84
CEPEC	8.34	15.69	49.84	102.69	101.34
Control overhead (times)					
FLHF	2.617	3.97	3.825	4.185	4.424415
FL	2.599	3.361	4.166	4.174	4.438866
CVIA	4.235	4.692	5.174	5.392	5.685777
CEPEC	4.24	4.678	4.972	5.191	5.475912
Call dropping probability (%)					
FLHF	2.2%	4.5%	6.3%	5.4%	8.5%
FL	3.9%	4.7%	9.4%	8.7%	10.2%
CVIA	8.9%	9.8%	21.6%	32.2%	39%
CEPEC	10.5%	11%	16.4%	17.4%	27.7%
Call blocking probability (%)					
FLHF	5.6%	12.6%	16.7%	19.2%	22.8%
FL	6.1%	12.1%	17.3%	20.1%	25.4%
CVIA	5.1%	11.7%	27.8%	36.6%	38.6%
CEPEC	4.3%	13.9%	26.5%	33.1%	34.2%
End-to-end delay (ms)					
FLHF	1(ms)	2(ms)	8(ms)	7(ms)	7(ms)
FL	1(ms)	6(ms)	17(ms)	10(ms)	12(ms)
CVIA	11(ms)	33(ms)	55(ms)	75(ms)	94(ms)
CEPEC	28(ms)	71(ms)	148(ms)	178(ms)	211(ms)

Table 3: Overall comparison of the experiment results for the four schemes.

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