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Information theory based performance analysis and enhancement of Safety applications and cluster design in VANET

Zhongyi Shen *[,1], Xin Zhang[1], Meng Zhang[1], Zhihao Chen[1], Weijia Li[1], Hongyu Sun[1]

[1]School of Information and Communication Engineering Beijing University of Posts and Telecommunications PO Box93, 10 XiTuCheng Rd, HaiDian, Beijing, CHINA

Abstract

Safety applications in vehicular ad hoc network (VANET) are handled by broadcast to disseminate safety related messages, due to lack of stable topology. The mobility of vehicles leads to significant performance degradation, especially in dense and dynamic scenarios. This paper presents an information theory based mobility model to determine the theoretical amount of information for VANET safety applications. The new mobility model considers the safety distance and vehicle's status. Analysis results are helpful in reducing redundant information and gaining more insight for system design. Based on the model, an adaptive algorithm to derive the optimal data rate is proposed. In addition, an adaptive control channel interval (CCI) algorithm is applied in cluster forming to improve stability of cluster topology. Numerical simulations based on NS-3 show that algorithms proposed can improve the performance dramatically, and the effectiveness of the safety requirements is guaranteed.

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Keywords: Mobility, information theory, cluster, vehicular ad hoc network (VANET), Dedicated Short-Range Communication (DSRC)

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1. Introduction

The VANET is a self-organizing network that works on vehicular communications. New technologies like Dedicated Short-Range Communications (DSRC) are in support of advanced vehicular safety applications to improve traffic efficiency for vehicular transportation. Growing attention from researchers and transportation industry has been driven by DSRC technology which employs IEEE 802.11p and IEEE 1609 standards for its capability to improve the traffic safety via various safety applications, through vehicle-to-vehicle (V2V) and vehicle-to infrastructure (V2I) communications.

*Corresponding Author. E-mail: szy823804813@bupt.edu.cn

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The core of the DSRC-based applications are safety applications, including periodic broadcast and emergency message dissemination which are used for cooperative collision avoidance (CCA), and it's the primary motivation for deploying DSRC. Periodic broadcast messages containing safety information such as position, velocity etc. are disseminated among vehicles with DSRC-based equipment, and the message received form DSRC-equipped neighbors can be used to locate the vehicle in a collision threat or in blind spot. An emergency message will be send when accidents like collision or a sudden brake are detected. The U.S. Department of Transportation (DOT) has estimated that vehicle-to-vehicle (V2V) communication based on DSRC can address up to 82% of all crashes in the United States involving unimpaired drivers, potentially saving thousands of lives and billions of dollars [1].

The U.S. Federal Communications Commission allocated 75MHz of licensed spectrum in the 5.9 GHz band for DSRC [2], and the spectrum is divided in to seven 10-MHz channels, including a control channel (CCH) for control message and safety related applications, and six service channels (SCH) which will be used for non-safety applications. In order to ensure that all the control messages and safety messages won't be missed, DSRC devices will follow a synchronization procedure. A synchronization interval comprises a CCH interval, followed by a SCH interval. During the CCH interval, devices will tune to the CCH for safety applications and service announcement, and the SCH offered will be indicated. To handle time-critical safety applications, the broadcast mode is considered to be a highly appropriate technique for safety messages dissemination [3]. In this paper, safety-related information will be broadcast at a certain frequency, and a broadcast-based retransmission mechanism [4] is introduced to improve reliable of event-driven emergency message dissemination.

The mobility of vehicles determined by the density, velocity and drivers' behaviors is an essential part in analyzing VANET applications. The rapidly changing network topology resulting from the uncertainty of the vehicle's state can exercise a great influence on system performance. At high density scenario, there are a large amount of devices in the transmission range of each vehicle, which will leads to significant performance degradation of IEEE 802.11p Carrier Sense Multiple Access (CSMA) and serious channel congestion [5]. The latency and low reliability resulting from the channel congestion and packets collision in medium access control (MAC) Layer will impact the broadcast based safety applications. Due to lack of request-to-send/clear to- send (RTS/CTS) process in IEEE 802.11p broadcast mode, the reliability of the transmission of event-driven emergency messages will decrease.

Numerous congestion control algorithms in MAC layer have been proposed to improve the performance in dense and high mobility situation. Rate control schemes have been investigated extensively when the fixed beacon frequency which is broadcasted every 100ms may result in a large number of collisions, especially in high density networks. But seldom has the mobility of vehicles been considered, the influences of safety applications associated with the reduction of data rate. Clustering is another effective approach to increase the VANET capacity. Cluster members will perform in a non-competitive manner controlled by a cluster head. The main challenge in clustering is to maintain the stability of cluster with the rapid change of the vehicle's states. The high-frequency change of VANET topology will introduce high overhead and low throughput, and it will need more time for the access process.

This paper proposes a new mobility analytical model, taking into consideration the probability of the change of motion in different density and velocity, which can reflect the mobility of vehicles more realistically. Then a novel information theory based rate control algorithm is introduced to obtain the theoretical optimum of messages rate to reduce redundant broadcast messages on the premise of the reliability of security under different scenarios. Entropy will be used in the rate control algorithm to measure the uncertainty based on the probabilistic model we derived. Based on the mobility model, a cluster-based adaptive CCI algorithm is proposed to derive the optimum amount of information needed to maintain the stability of clusters theoretically. The algorithm is employed in a more flexible cluster-based system designing considered the mobility of vehicles. Simulation results show that the proposed rate control algorithm can enhance the performance of DSRC system and make a good trade-off between the safety requirements and system performance in terms of delay and packet loss rate, aggravated by redundant broadcast messages which have little effects on safety applications, and the adaptive CCI algorithm shows significant gain in maintaining the stability of clusters by introduced a more flexible cluster design in various scenarios. The cluster can adopt a more suitable size to reduce the frequent network topology change. The main contributions of the algorithm is deriving accurately the relationship between the vehicle's mobility and CCI of cluster-based system to improve the stability, and the specific clustering methods are not discussed in this paper.

The rest of the paper is organized as follows. Section 2 reviews related work. Section 3 describes the mobility analytical model. In Section 4, the information theory based rate control algorithm is described along with the theoretical derivation based on the mobility model we proposed. In Section 5, the cluster-based adaptive CCI algorithm is given based on the mobility analysis. Simulation results are given in Section 6 to verify the performance and accuracy of algorithms proposed, and Section 7 presents the conclusion.

2. Related work

The MAC layer congestion issues have been investigated extensively. Numerous theoretical and simulation-based analyses show the impact of high density on latency and packet successful reception rate [6],[7]. A centralized approach and a distributed approach are proposed in [8] to adapt the window size without considering the mobility of vehicles. The study in [9] illustrates that high traffic of periodic broadcast messages may reduce the resource availability for the emergency messages. A Markov model is used in the article to analyze the dissemination delay of event-driven emergency messages in the presence of low-priority periodic messages, but no specific algorithm is proposed to determine a good tradeoff to improve the performance and the mobility of vehicles is overlooked. [10] describes a DSRC congestion control scheme, based on maximizing channel throughput via distributed control of the safety message rate. Hafeez et al. in [6] propose a mobility model considering the threshold distance to avoid collision in different vehicle density indicated by a Poisson arrival queue. In [11], an adaptive rate control algorithm is proposed, which takes into account the prediction deviation of the motion of nearby vehicles. The broadcast will be deferred when the predicted positions satisfy the feasibility condition in consecutive slots. Few works have been done to consider the threshold distance in mobility models. Hafeez in [6] introduces the threshold distance in the initial distribution of vehicles, but the state of each vehicle is considered to be constant and independent. The majority of studies of congestion control in safety-related message focus on the performance improvement of delay and throughput. There have been no studies to explore the theoretical optimum of messages rate control on the premise of the reliability of security.

For the problems in terms of low reception ratio, high delay, and channel congestion of IEEE 802.11p which have been studied extensively in [12–15]. Considerable cluster-based protocols have been proposed to improve the performance in VANET. The authors in [16] proposed a cluster-based scheme using the contention-free MAC within a cluster and the contention-based IEEE 802.11 MAC among cluster-head vehicles with two transceivers operating on different channels armed by each vehicle. The TDMA used in the system needs strict synchronization among all vehicles. Moreover, the status change due to the vehicle's mobility is neglected. A distributed multichannel and mobility-aware cluster-based MAC (DMMAC) protocol is proposed in [17]. Vehicles will send different types of message to form cluster and update their safety information. To guarantee all cluster members send their safety messages successfully during the CCI which is fixed as 100ms, the communication range will be decreased to reduce the members in the cluster in high density scenarios, which will lead to frequent change of VANET topology, and the structure of clusters will become unstable in real traffic. The majority of studies of cluster-based algorithms do not consider the impact on the stability of clusters introduced by the mobility of vehicles, and the exploration on the theoretical amount of information needed to maintain the stability of clusters is neglected in existing cluster-based system design.

3. Mobility model

Modeling the mobility of vehicles realistically is an essential and challenge task since the movement of the vehicle is determined by many factors such as the traffic density, the vehicles velocity and driving habits. Most related researches on vehicles mobility model neglect or simplify the changing status of vehicles caused by the traffic condition, driver's behavior. And the motion status is considered unchanged and independent throughout the entire process, which is unrealistic. In this paper, a new mobility model is proposed, considering the probability of status changes in different scenarios.

The proposed mobility model is based on a one-way one-lane highway scenario, which can be extended to other more complicated scenarios. Since the transmission range is much larger than the wide of the road, the highway scenario is abstracted into a 1-D model. Vehicles will follow the direction of the road with a speed uniformly distributed between V_{min} and V_{max} [18]. The Poisson process is widely adopted as a sufficiently accurate assumption for modeling the vehicle arrival process in the highway scenario [3]. Vehicles in the highway scenario follow Poisson point process with density β (in terms of vehicles per meter), and the vehicles spacing satisfies the exponential distribution. The probability distribution function (pdf) of vehicles spacing S is given as

$$f(s) = \beta e^{-\beta s}, s > 0. \tag{1}$$

The safety distance D_s is taken into account, which is determined by the current speed V and the reaction time T_r . And the safety distance is given as

$$D_s = V \times T_r. \tag{2}$$

To avoid collision caused by a sudden stop from the vehicle in front, the driver will decelerate when the distance from the vehicle ahead is detected smaller than the safety distance. At an arbitrary point in time, to find the probability that the vehicle will decelerate to keep a safety distance, the distributions of vehicle's density and speed are assumed constant is a certain period of time compared with the time of the communication process. Because the density and the speed are independent, the probability that the vehicle will decelerate at an arbitrary point in time can be described as

$$\begin{aligned} P_d &= \iint\limits_{s<T_r\times V} f(s)\frac{1}{V_{max}-V_{min}}\mathrm{d}s\mathrm{d}v \\ &= \frac{e^{-\beta T_r(e^{-V_{min}}-e^{-V_{max}})}}{\beta T_r(V_{max}-V_{min})}. \end{aligned} \tag{3}$$

The probability of deceleration in a poor traffic condition with dense traffic and high speed is derived in (3), which means that the vehicles dynamic states are frequently changed, consistent with the actual traffic situation. On the contrary, a vehicle prefers to remain the current state when the traffic condition is good. In the case that a vehicle won't decelerate, it will remain the current speed or accelerate with the probability of $1 - P_d$. In this situation, the probability of accelerate is assumed to be proportional to P_d, which means that the probability of acceleration will increase with P_d in a good traffic condition, and will decrease when P_d is high. Based on the assumption and analysis above, the probability of acceleration can be written as

$$P_a = P_d(1 - P_d). \tag{4}$$

And the probability that a vehicle remains the current state is

$$P_r = 1 - P_d - P_a. \tag{5}$$

From (3), (4) and (5), it's clear that vehicles are more likely to accelerate or decelerate in the high-density and high-speed scenario, which means the vehicle's status will change frequent in mess road conditions for security.

Based on the analysis above, the motion of a vehicle is divided in time slots of Δt, during which the state of the vehicle is assumed to remain. The state can be changed at the beginning of a new time slot with the probability derived in the mobility model. To simplify the analysis, the acceleration is assumed to be a fixed value. Then the probability distribution of acceleration of the vehicle in the n_i slot based on (3), (4) and (5) is

$$a = \begin{cases} a, & P_a \\ 0, & P_r \\ -a, & P_d \end{cases} \tag{6}$$

The speed of the vehicle at the end of the n_i slot is

$$V_i = V_{i-1} + a_i\Delta t. \tag{7}$$

The distance the vehicle travels during the n_i slot can be written as

$$S_i = V_{i-1}\Delta t + \frac{1}{2}a_i\Delta t^2. \tag{8}$$

At the starting point t_0, the vehicle locates at X_0 with the speed V_0. Substituting the speed in the reference point t_0, the speed of the vehicle at the end of the n_i slot is given as

$$\begin{aligned} V_i &= V_{i-1} + a_i\Delta t \\ &= V_0 + \sum_{k=1}^{i} a_k\Delta t. \end{aligned} \tag{9}$$

And the total distance in $N\Delta t$ from t_0 is

$$\begin{aligned} S_{N\Delta t} &= \sum_{i=1}^{N} S_i \\ &= \sum_{i=1}^{N} V_{i-1}\Delta t + \frac{1}{2}a_i\Delta t^2. \end{aligned} \tag{10}$$

Substituting (9) in (10), we have

$$\begin{aligned} S_{N\Delta t} &= \sum_{i=1}^{N}(V_0 + \sum_{k=1}^{i-1} a_k\Delta t)\Delta t + \frac{1}{2}a_i\Delta t^2 \\ &= NV_0\Delta t + \sum_{i=1}^{N}(N-i)a_i\Delta t^2 + \frac{1}{2}a_i\Delta t^2 \\ &= NV_0\Delta t + \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i\Delta t^2. \end{aligned} \tag{11}$$

4. Analytical model and information theory based control algorithm

The Basic Safety Message (BSM) format [19] is utilized in the periodic broadcast messages of DSRC safety applications. The safety related messages are transmitted over 300-500 meters, with a 6 Mbps data rate, and a 10 Hz message rate by default [20],[21]. The redundancy introduced by the fixed message rate scheme when the broadcast messages are excess to support safety applications will aggravate network traffic and increase the probability of packets loss and the packets delay, especially in dense and high-mobility conditions. The performance degradation can severely impact the time-critical safety applications.

In this section, an information theory based rate control algorithm is proposed based on the mobility model in section 3 to analyze the optimum rate control scheme in substance. The entropy will be utilized to measure the uncertainty of vehicles position caused by the distribution of spacing and the mobility of vehicles based on the probabilistic model we derived.

The time a state packet is received from the target vehicle serves as a reference point t_0, and the speed and the position can be obtained from the received packet. The total distance $S_{N\Delta t}$ in $N\Delta t$ from t_0 can be derived from (11).

Assume that no state broadcast packet is received from the target vehicle since t_0, so the position prediction at $N\Delta t$ is based on the safety information obtained from the most recently received packet at t_0. The predicted position of the vehicle at $N\Delta t$ is

$$\tilde{S}_{N\Delta t} = NV_0\Delta t. \tag{12}$$

Combining (10) and (11), the deviation of the prediction about the position of the vehicle at $N\Delta t$ is

$$S_{N\Delta t} - \tilde{S}_{N\Delta t} = \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i\Delta t^2. \tag{13}$$

Because of the motion in every slot is independent, the deviation of prediction is composed of N independent variables as

$$S_{N\Delta t} - \tilde{S}_{N\Delta t} = \sum_{i=1}^{N} X_i \tag{14}$$

$$X_i = (N - i + \frac{1}{2})a_i \Delta t^2. \tag{15}$$

According to the Liapunov central limit theorem, the deviation of prediction is approximate normal distribution.

$$S_{N\Delta t} - \tilde{S}_{N\Delta t} = \sum_{i=1}^{N} X_i \sim N(\mu, \sigma^2). \tag{16}$$

where μ and σ^2 are summations of the mean and variance of each independent variable X_i. According to the probability distribution of the acceleration in (6), μ and σ^2 can be expressed as

$$\begin{aligned} \mu &= \sum_{i=1}^{N} EX_i \\ &= \sum_{i=1}^{N} (N - i + \frac{1}{2})a_i \Delta t^2 (P_a - P_d) \\ &= \frac{N^2 a_i \Delta t^2 (P_a - P_d)}{2}. \end{aligned} \tag{17}$$

$$\begin{aligned} \sigma^2 &= \sum_{i=1}^{N} DX_i \\ &= \sum_{i=1}^{N} P_a[(N - i + \frac{1}{2})a_i \Delta t^2]^2 + P_d[(N - i + \frac{1}{2})a_i \Delta t^2]^2 \\ &= \frac{(P_a + P_d)a^2 \Delta t^4 (4N^3 - N)}{12}. \end{aligned} \tag{18}$$

From (16), (17) and (18), it is clear that the accuracy of prediction decreases with the number of time slots. To guarantee the performance of safety applications in vehicles positioning and collision warning, the threshold E_{th} of the deviation of position prediction is set as 0.5m based on the analysis in [22]. Therefore, the probability that the positioning deviation of the target vehicle is less than the threshold is given by

$$\begin{aligned} &P\{|S_{N\Delta t} - \tilde{S}_{N\Delta t}| \le E_{th}\} \\ &= \Phi(\frac{E_{th} - \mu}{\sigma}) - \Phi(\frac{-E_{th} - \mu}{\sigma}). \end{aligned} \tag{19}$$

In this paper, we consider that ensuring the positioning deviation less than the threshold with 95% probability is acceptable. Based on the analysis above, we get

$$\Phi(\frac{E_{th} - \mu}{\sigma}) \approx \Phi(2). \tag{20}$$

$$\sigma_{th} \approx \frac{E_{th} - \mu_{th}}{2}. \tag{21}$$

To measure the uncertainty of the positioning deviation, the entropy of the uncertainty Y at $N\Delta t$ is

$$H(Y) = ln(\sigma_N \sqrt{2\pi e}) \tag{22}$$

where σ_N is the standard deviation of the distribution at $N\Delta t$.

From (20) and (21), the threshold of the entropy at $N\Delta t$ is $ln(\sigma_{th}\sqrt{2\pi e})$. Assume that a state packet is received at $N'\Delta t$ during t_0 to $N\Delta t$, the conditional entropy is

$$H(Y|X) = ln(\sigma_{Y|X} \sqrt{2\pi e}) \tag{23}$$

where $\sigma_{Y|X}$ is the standard deviation of the distribution at $N\Delta t$ when a state packet is received at $N'\Delta t$.

To satisfy the threshold of the entropy, we get the inequality

$$\sigma_{Y|X} \le \sigma_{th}. \tag{24}$$

$$\begin{aligned} \sigma_{Y|X}^2 &= \sum_{i=1}^{N-N'} DX_i \\ &= \frac{(P_a + P_d)a^2 \Delta t^4 [4(N - N')^3 - (N - N')]}{12}. \end{aligned} \tag{25}$$

Substituting (25) in (24), the maximum transmission interval $(N - N')\Delta t$ under the given density and velocity distribution can be derived.

5. Analytical model and adaptive cluster-based CCI algorithm

Most cluster-based scheme in VANET use contention-free MAC method within a cluster and the contention-based MAC method among different clusters through the cluster-head. The selected cluster-head will collected safety information containing velocity, position.etc. within a CCI, and the aggregated message will be disseminated to cluster members and neighbor clusters. Due to the contention-free MAC method within a cluster, the cluster size have to be limited to allow all the members to transmit safety messages within a CCI successfully. In high-density scenarios, relevant algorithm is necessary to decrease the cluster range as to reduce the number of cluster members, otherwise, some messages will be missed for the capability deficit with lots of vehicles in the cluster range. Nevertheless, the frequent change of VANET topology will introduce high overhead and low throughput, and it will need more time for the access process.

The CCI of existing cluster-based schemes [16, 17] is set to 100ms as a constant value, in accordance with the beacon interval in IEEE 802.11p. The inflexible design will introduce redundant information and reduce the capability of clusters, particularly in high-density scenarios. In this section, analysis based on the mobility model is given to derive the theoretical relationship between the vehicle's mobility and cluster stability, and an adaptive cluster-based CCI algorithm is proposed to obtain the optimum CCI in different scenarios. The major contribution of the algorithm is to analysis the influence of mobility characters in VANET on cluster stability, while the specific clustering methods are not discussed in this paper.

The analysis model is built based on a one-way multilane highway segment. The movement of vehicles in each lane is considered to be independent. Assume that vehicles in the lane have been clustered in a certain method, which has no influence on the analyze model, and C_h and C_t are the head and tail of a valid cluster at t_0, when the cluster head is aware of all the members in the cluster. The velocity of C_h and C_t at t_0 is V_0^h and V_0^t, which follow uniform distribution in section 3. The total distance of C_h and C_t in $N\Delta t$ from t_0 based on (11) are

$$S_{N\Delta t}^h = NV_0^h\Delta t + \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^h\Delta t^2. \tag{26}$$

$$S_{N\Delta t}^t = NV_0^t\Delta t + \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^t\Delta t^2. \tag{27}$$

The change of the cluster range in $N\Delta t$ is

$$\begin{aligned} &S_{N\Delta t}^h - S_{N\Delta t}^t \\ &= NV_0^h\Delta t - NV_0^t\Delta t + \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^h\Delta t^2 \\ &-\sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^t\Delta t^2. \end{aligned} \tag{28}$$

Let U=$NV_0^h\Delta t$ - $NV_0^t\Delta t$, because V_0^h and V_0^t are independent from each other, the probability density function (PDF) of U is solved as

$$f(U) = \begin{cases} \dfrac{(V_{max}-V_{min})N\Delta t - U}{(V_{max}-V_{min})N\Delta t^2} & 0 \le U < (V_{max}-V_{min})N\Delta t \\ \dfrac{(V_{max}-V_{min})N\Delta t + U}{(V_{max}-V_{min})N\Delta t^2} & (V_{min}-V_{max})N\Delta t \le U < 0. \end{cases} \tag{29}$$

From (28),we set

$$\begin{aligned} X_{Joint} &= \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^h\Delta t^2 - \sum_{i=1}^{N}(N-i+\frac{1}{2})a_i^t\Delta t^2 \\ &= \sum_{i=1}^{N} X_i^h - \sum_{i=1}^{N} X_i^t. \end{aligned} \tag{30}$$

Where $\sum_{i=1}^{N} X_i^h$ and $\sum_{i=1}^{N} X_i^t$ follow normal distribution. On account of the movements of C_h and C_t are independent. From(16),(17)and(18),it can be derived that X_{Joint} has a normal distribution as

$$X_{Joint} = \sum_{i=1}^{N} X_i^h - \sum_{i=1}^{N} X_i^t \sim N(2\mu, 2\sigma^2). \tag{31}$$

Where μ and σ is described in (17) and (18).

Based on the analysis above, the change of the cluster range in $N\Delta t$ is U+X_{Joint}. The structure of a cluster is considered to be changed when a member leave the range or a new vehicle fall within the cluster range. The cluster head has to update the information of cluster members to detect the leaving member or the vehicle applying to join the cluster. On the basis of the mobility model, it is considered that the structure change when the variation of the cluster range is greater than the vehicles spacing S which satisfies the exponential distribution in (1), and the cluster head is assumed in the centra of the cluster consistently. The probability that the variation of the cluster range is greater than the vehicles spacing is

$$\begin{aligned} P_c &= P\{|U + X_{Joint}| \ge S\} \\ &= \iiint_{|U+X_{Joint}|\ge S} f(u,x,s)\mathrm{d}u\mathrm{d}x\mathrm{d}s. \end{aligned} \tag{32}$$

Where P_c is a function of N. To update the cluster member promptly and guarantee the security, the probability that the structure of the cluster remained $1-P_c$ should greater than a threshold value P_{th}. When there is L lanes on the highway, the following inequality should be satisfied.

$$(1-P_c)^L \ge P_{th}. \tag{33}$$

Substituting (32) in (33), the maximum update interval in different density and velocity is derived, which is considered as the adaptive CCI, varied in different scenarios. To verify superiority of the adaptive CCI algorithm, it is applied in DMMAC proposed in[17]. There are 4 types of messages in DMMAC, containing status, invitation and consolidated messages sent from cluster members or cluster head. The upper bound of transmission time is given in [17] as

$$(T_{avg})_{ub} = T_{cf} + [T_{mf}] + (2\beta R - 1)[T_m] + [T_{in}] + [T_{cl}]. \tag{34}$$

Where T_{cf} , T_{mf} and T_m are the transmission times of the first messages sent by the cluster head and members, and T_{in} ,T_{cl} are the transmission times of invitation and the last message. To enable all cluster members to transmit successfully their safety messages during the CCI, authors describe the condition that

$$(T_{avg})_{ub} \le \varphi \times CCI. \tag{35}$$

Analysis and simulation results in [17] illustrate that the cluster need to decrease the range to reduce the nodes within the cluster in order to satisfied (35). The transmission range decrease form 300m to

Table 1. Value of parameters used in Simulation

Parameter	Value
Length of highway segment	2000m
Vehicle's speed	80-120km/h
Vehicle's density	0.01-0.1vehicle/m
Frequency	5.9GHz
Packet size	100Bytes
Transmission power	50mW
Received power threshold	3.162e-13W
Noise floor	1.26e-14W
DIFS	64μs
Antennas gain	1
Reaction time	1s
Δt	100ms

100m when the density reaches 0.25 vehicles/m. We apply the adaptive CCI algorithm proposed in this paper, the numerical results demonstrate the advantage over DMMAC in maintain the cluster size in high density scenarios to keep the stability of the cluster. Moreover, the redundancy is reduced to support other control messages. The numerical results is given in the simulation part.

6. Model validation and simulation

In this section, the theoretical results of the optimal periods under various conditions and the adaptive cluster-based CCI algorithm proposed in section 4 and section 5 are shown. The performance of the rate control scheme introduced in the paper is evaluated in terms of the accuracy of positioning, the packet loss rate and the average delay. The stability of the adaptive CCI algorithm in section 5 which is essential in clustering design is tested, compared with DMMAC in [17] and the CMCP in [16].

The well-known simulator NS3 [23] (version 3.22) is used to analyze the system's performance. The Nakagami propagation model is used in simulations, which is considered best for vehicular environment in many research [24], [25]. The simulation scenario is based on one-direction four-lane highway segment, with the velocity of vehicles ranges from 80-120 km/h, which is typical for highways. The simulation parameters are summarized in Table 1.

Figure 1 shows the optimal period of the broadcast messages which can be calculated from (24) and (25) under different vehicle density and velocity distributions. From the numerical results in Figure 1, it can be observed that the value of the broadcast period is significantly different under various conditions. The fixed rate control scheme can't meet the changing safety requirements and redundancy will be introduced in some circumstances.

Figure 2 shows the accuracy of the position prediction through the periodic broadcast messages with the rate

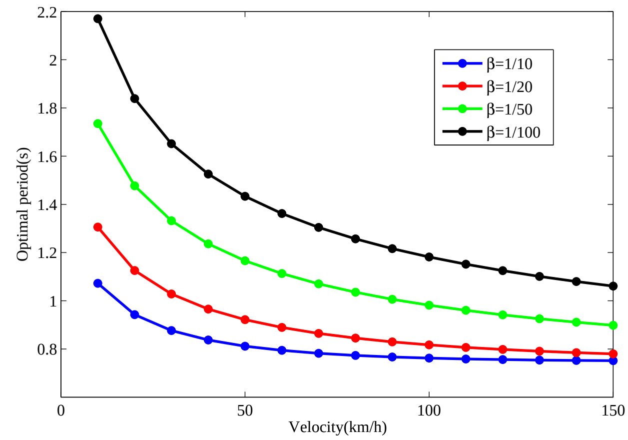

Figure 1. Optimal periods of the broadcast messages under different vehicle density and velocity distributions

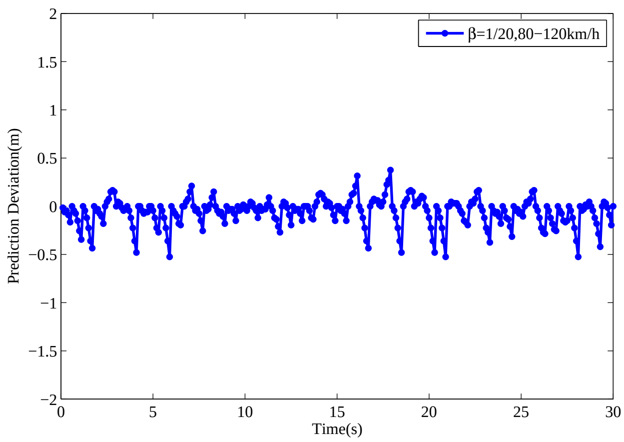

Figure 2. Prediction deviation with β=1/20,speed ranges from 80-120km/h

control scheme we proposed. The motion of the vehicle is based on the mobility model in Section 3. The vehicles spacing satisfy the exponential distribution with $\beta = 0.05$, and the speed ranges from 80-120km/h as mentioned.

Figure 3 and Figure 4 show, respectively, the packet loss rate the packet delay versus vehicle density ranged from 0.01 to 0.1 vehicles/m in (1), with and without the entropy-based rate control algorithm. As is shown in Figure 3, the packets loss caused by collisions from neighboring vehicles and hidden terminals will become serious with the increase of vehicle density, which will leads to undesirable performance, particularly in dense vehicular environment. At the same time, vehicles will take longer time to access the channel to broadcast the state messages, and the packet delay increases with the increasing of vehicles density. The high packet loss rate and packet delay will be a disaster to safety

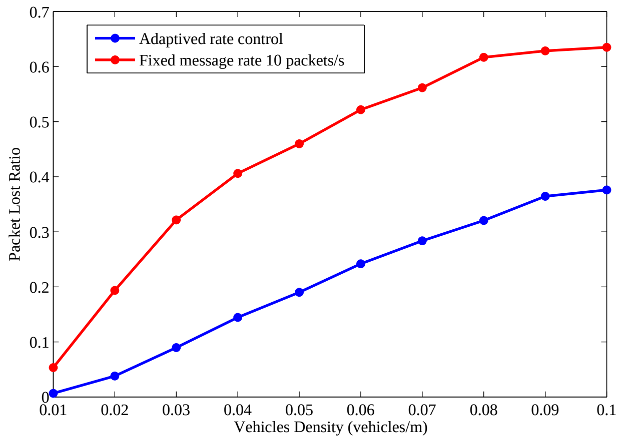

Figure 3. Packet loss rate versus vehicle's density

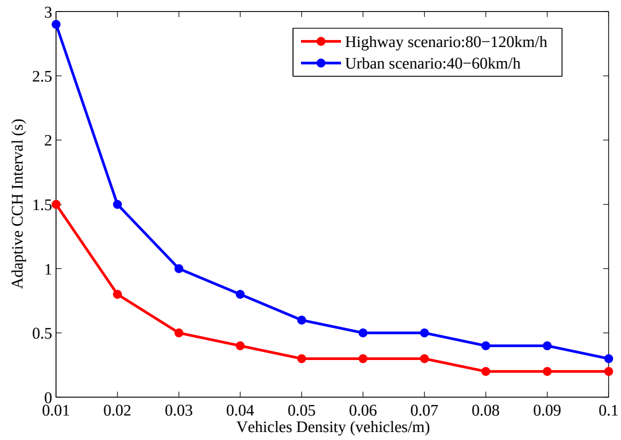

Figure 5. Adaptive CCI versus vehicle's density

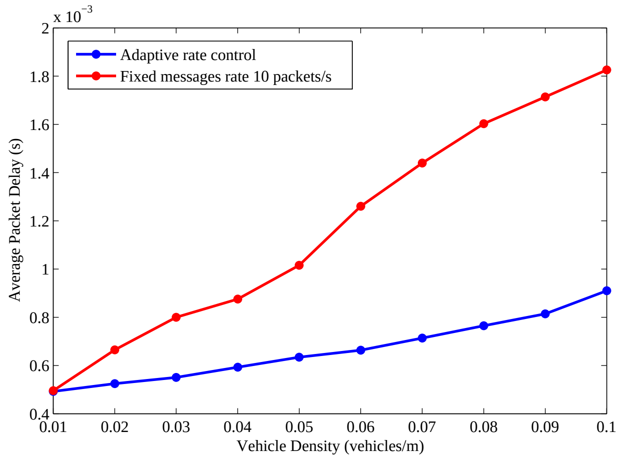

Figure 4. Packet delay versus vehicle's density

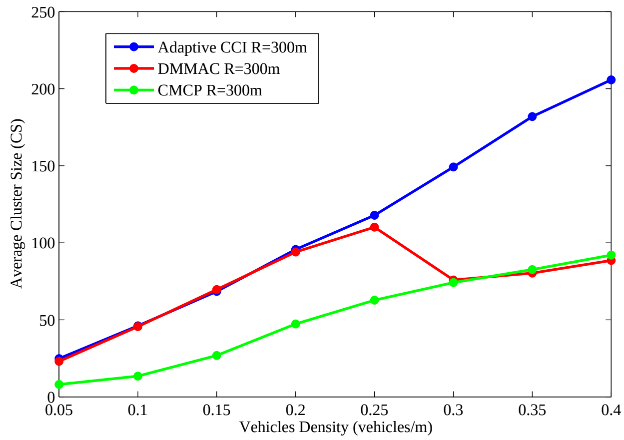

Figure 6. Cluster size versus vehicle's density

applications. Adapting the entropy-based rate control algorithm, the packet loss rate and packet delay are improved greatly, as is shown in the figure. It is obvious that the entropy-based rate control scheme outperforms fixed-rate and other rate control schemes not only for the improvements of network performance, but also the consideration to the safety requirements. The theoretical results of the adaptive cluster-based CCI in highway and urban scenarios are shown in Figure 5. Compared with the typical highway scenarios with the velocity ranging from 80-120km/h, vehicles in urban scenarios have more coincident and low speeds range from 40-60km/h. The threshold probability P_{th} is set as 90%. It can be seen that the value of the adaptive CCI is significantly different under various density, and clusters in urban scenarios have a longer CCI for a more coincident speed distribution, with means the structure of a cluster is less likely to change. The adaptive CCI algorithm has a more flexible CCI considering safety requirements compared with the fixed CCI in existing works, and the redundancy is reduced to support other control messages.

Figure 6 shows the numbers of vehicles in the cluster range in different density compared with the DMMAC in [17] and the CMCP in [16]. It is clear that the cluster size in DMMAC has a abrupt change with the transmission switching to 100m when the density reaches 0.25 vehicles/m. The cluster stability will decrease when decreasing the communication range. Moreover, the frequent change of cluster range will introduce high overhead. Many vehicles have to wait for complicated procedures to access the channel again due to the sudden change of the cluster range. It can be observed that the adaptive cluster-based CCI can improve the capability of clusters and the safety requirements are guaranteed at the same time.

7. Conclusions

In this paper, a new mobility model has been presented in which the change of motion under various vehicle densities and speeds is considered. Entropy is used to describe the uncertainty of the vehicle position caused by the change of motions. An information theory based rate control algorithm is proposed to derive the optimum broadcast period. Adapting the rate control algorithm, vehicles are able to adjust the broadcast period of states messages to improve the performance of safety applications. Moreover, a theoretical model is proposed to analyze the stability of clusters considering the mobility of vehicles, and an adaptive cluster-based CCI algorithm is proposed to improve the stability of clusters in VANET. The adaptive cluster-based CCI can improve the capability of clusters to enhance the cluster stability and reduce redundant information compared with existing works. Simulation results in NS3 show that the proposed rate control algorithm can significantly reduce redundancy, thus reducing the packet delay and packet loss rate, and the accuracy of vehicle positioning is guaranteed at the same time. The adaptive cluster-based CCI shows a more flexible system design and the performance in maintain the cluster size. The information theory based analysis of measuring the uncertainty provides new insights on system design for novel networks with high mobility and high intelligence, and it can be applied in other heterogeneous networks like LTE-based vehicular communications in future works.

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