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Improving beacon dissemination in VANETs – a cyber-physical system based design

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***Abstract*—One critical issue for vehicular safety applications is how to timely and reliably disseminate kinetic information, known as *beacon*, among vehicles. In this paper, we try to improve the beacon dissemination performance in vehicular ad hoc networks (VANETs) especially in drastic disturbance scenarios. To this end, a decentralized beacon dissemination control scheme (DBDCS) is proposed from the cyber-physical system perspective, where both the vehicle dynamics and VANET behaviors are jointly considered. In the envisioned scheme, the control channel interval for beacon dissemination can be adaptively adjusted based on both the current local traffic dynamics and the networking situation. Numerical results show that the proposed scheme can significantly improve the beacon dissemination performance especially in disturbance scenarios.**

I. Introduction

The emerging vehicular ad hoc networking (VANET) techniques facilitate various cooperative vehicular safety applications in modern intelligent transportation systems. One critical issue for the safety applications is that each vehicle is supposed to periodically disseminate its current kinematic status (including position, velocity, acceleration, etc.) to neighboring vehicles, namely *beacon message dissemination*. In the IEEE 1609.4 standard, the channel access time is divided into synchronized intervals (SI). Each SI contains a guard interval and an alternating fixed-length interval, including the control channel interval (CCHI) and the service channel interval (SCHI). Thus a vehicle can send both the beacon message during CCHI and infotainment information during SCHI on a single-radio interface.

However, the ratio of CCHI and SCHI is fixed in the current IEEE 1609.4 standard, which could introduce adverse effects, such as the lower beacon reception rate in dense traffic conditions and the risk of starvation for non-safety bulky data in sparse traffic flow. To alleviate these deficiencies, previous studies have proposed different schemes to optimize beacon dissemination, which can be classified according to the controlled system parameters: beacon frequency control, beacon dwelling time control, transmit power control, contention window control, and the joint control of the aforementioned methods [1], [2]. Nevertheless, most work only focuses on the performance of a slow-varying system (i.e., the stable traffic flow with less difference velocity among vehicles and the stable networking status), seldom considering the system performance in the transient traffic states such as the drastic traffic disturbance scenarios. In a typical traffic disturbance, the beacon dissemination demands not only stable reception ratio but also quick response to the changing traffic conditions.

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To this end, we focus on improving the transient performance of beacon dissemination in drastic disturbance scenarios. We propose a decentralized beacon dissemination control scheme (DBDCS) from the cyber-physical system perspective, where both vehicle dynamics and VANET behaviors are jointly considered. The main idea for the envisioned scheme is that CCHI duration is dynamically adjusted based on the current local networking situation as well as the traffic condition. The local traffic density and networking status are explored by car-following models, which have not been fully investigated in previous work.

In Section II, we elaborate the proposed DBDCS to improve beacon dissemination specifically in disturbance scenarios. In Section III, we present numerical results, before concluding the paper in Section IV.

II. Beacon Congestion Control Scheme

A. Beacon Dissemination Control Scheme

The beacon reception rate (BRR) for a vehicle j (denoted B_j) is defined as the ratio of the received beacons M_j in one CCHI to the total target transmitted beacons N_j:

$$B_j = \frac{M_j}{N_j} \tag{1}$$

Since each vehicle only broadcasts one beacon in every CCHI, N_j is equal to the total neighbors of vehicle j within the transmission range.

In this paper, the objective of the envisioned DBDCS is to possibly maintain the BRR of a vehicle at the target value B_T in various traffic scenarios, which is critical prerequisite for vehicular safety applications. Intuitively, prolonging CCHI can improve BRR in dense traffic condition, while shortening CCHI may aggravate the channel congestion and accordingly

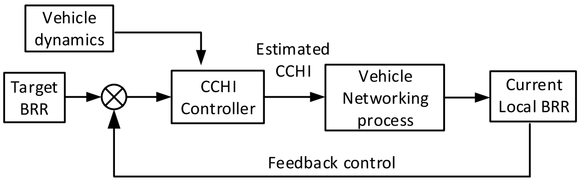

Fig. 1. Block diagram of DBDCS

decrease BRR. Therefore, we choose CCHI as the critical parameter in the proposed DBDCS which is adaptively controlled to maintain BRR at around B_T. In addition, each beacon is uniformly disseminated during the available CCHI time, which in general outperforms the synchronous one disseminating all beacons at the beginning of CCHI [3].

The block diagram of DBDCS is illustrated in Fig. 1. The CCHI closed-loop controller is activated when there is difference between the target BRR and the current local BRR, which can improve the performance and robustness of the beacon dissemination system. Specifically, we take into account the impact of local traffic dynamics on the CCHI controller so that the designed controller can meet with the requirement of changing traffic conditions.

B. Vehicle Dynamics

To implement the DBDCS, we need to accurately and timely obtain the local vehicle's BRR at first. As a initial step for the study, we only consider the scenario that all identical vehicles driving on a single lane. Next, we first describe the traffic dynamics by the car-following model, and then estimate the local BRR based on the analysis of traffic dynamics.

Car-following model can effectively describe the strong interaction among adjacent vehicles in dense traffic conditions. In this paper, we apply the *Intelligent Driver Model* (IDM) [4] for vehicles, which is based on the stimulus-response approach and can be expressed as follows:

$$s_j^*(t) = s_0 + v_j(t)T_0 + \frac{v_j(t)\Delta v_j(t)}{2\sqrt{ab}} \tag{2}$$

$$a_j(t) = a\Big[1 - \Big(\frac{v_j(t)}{v_0}\Big)^4 - \Big(\frac{s_j^*(t)}{s_j(t)}\Big)^2\Big] \tag{3}$$

where $s_j^*(t)$ is the desired safety gap to the preceding vehicle, s_0 is the minimum distance for congested traffic, T_0 denotes the safety time gap, a is the maximum acceleration and b is the comfortable deceleration.

We can get the inter-vehicle spacing for stable traffic flow (i.e., $a_j(t) = 0$ and $\Delta v_j(t) = 0$) with velocity v_e:

$$s_e = \frac{s_e^*}{\sqrt{1 - \Big(\frac{v_e}{v_0}\Big)^4}} = \frac{s_0 + v_e T_0}{\sqrt{1 - \Big(\frac{v_e}{v_0}\Big)^4}} \tag{4}$$

Accordingly, traffic density ρ can be calculated by $\rho = 1/(s_e + l_0)$, where l_0 is the vehicle length. Combing with the fundamental traffic flow equation $Q = v_e\rho$, we can further derive the equilibrium relations among traffic flow Q, steady velocity v_e and traffic density ρ. For a given transmission range R, the expected N_j in stable traffic flow can be calculated by $N_j = 2R\rho$.

To approximately estimate N_j of Eq. (1) in disturbance scenarios, we conduct the similar derivation as in stable traffic flow. We first calculate the average velocity $\overline{v}_j$ of the vehicle j within the transmission range R and regard it as the steady velocity v_e, then derive local $\overline{\rho}_j$ and N_j. In practice, due to the imperfect channel and beacon collisions in VANET, we can only partly collect the kinetic information of neighbors and approximately estimate the average velocity $\widetilde{v}_j$. To reduce the abnormal value of $\widetilde{v}_j$ due to the uncertainty of VANET, we implement a first order low-pass filter on the average velocity $\widetilde{v}_j$:

$$\widetilde{v}_j(t) = \alpha\widetilde{v}_j(t) + (1-\alpha)\widetilde{v}_j(t-1), 0 < \alpha < 1 \tag{5}$$

where α is the filter coefficient. We then can further derive the approximate number of neighbors $\widetilde{N}_j$.

Based on the estimated $\widetilde{N}_j$, we can approximately calculate the local beacon reception ratio $\widetilde{B}_j$ in each CCHI.

C. DBDCS Algorithm

Based on the DBDCS illustrated in Fig. 1, we devise the CCHI feedback controller as follows.

At the end of each CCHI, $\widetilde{B}_j$ would be compared with the predefined target B_T. If $\widetilde{B}_j$ is smaller than B_T, CCHI will be prolonged to discount the channel access contentions. If $\widetilde{B}_j$ is larger than B_T, CCHI will be shortened to provide more time for SCH. As an initial step of the feedback controller design, a simple proportional controller for CCHI is expressed by:

$$CCHI_{t+1} = CCHI_t + K_p(B_T - B_t)\Delta_{CCHI} \tag{6}$$

where K_p is the coefficient of CCHI controller, Δ_{CCHI} is the constant incremental CCHI. Specifically, we consider the circumstance where most of neighbors are undergoing deceleration phase of a typical disturbance, because in this case the local traffic density may increase rapidly which could deteriorate the system metric of BRR. To tackle this issue, we add an adjustment to the control algorithm of Eq. (6):

$$CCHI_{t+1} = CCHI_t + K_p(B_T - B_t)\Delta_{CCHI} - K_a\widetilde{a}\Delta_{CCHI} \tag{7}$$

where K_a is the impacted coefficient of the average acceleration $\widetilde{a}$. In this equation, the factor $\widetilde{a}$ as the indicator of local traffic dynamics is taken into account, which can speed up the CCHI adjusting process. The pseudo-code of the DBDCS is shown in algorithm 1.

Note that due to decentralized adjustment of the CCHI for each vehicle, the switching points between CCH and SCH may be different among neighboring cars. We leave the impact of CCHI synchronization on the beacon dissemination performance in future work.

III. Numerical Results

To evaluate the performance of the proposed DBDCS, we conduct extensive simulation experiments by utilizing a software tool called Veins [5]. The simulation parameters for

Algorithm 1 DBDCS Algorithm

Input: Target BRR B_T, vehicular kinetic information
Output: Next beacon dissemination time

for each CCHI **do**
  Collect all received beacons M_j during CCHI;
  $\widetilde{v}_j(t) = \alpha\widetilde{v}_j(t) + (1-\alpha)\widetilde{v}_j(t-1)$; ▷ Calculate $\widetilde{v}_j$
  $\widetilde{a}_j(t) = \alpha\widetilde{a}_j(t) + (1-\alpha)\widetilde{a}_j(t-1)$; ▷ Calculate $\widetilde{a}_j$
  Estimate the expected $\widetilde{N}_j$;
  $\widetilde{B}_j = \widetilde{M}_j / \widetilde{N}_j$; ▷ Estimate the current$\widetilde{B}_j$
  Estimate the SMA $\widetilde{B}_j$
  ▷ Adaptively adjust CCHI upon current $\widetilde{B}_j$ and local traffic condition.
  if $\widetilde{B}_j < B_T$ and $\widetilde{a}_j(t) < 0$ **then**
    Estimate $CCHI$ by the controller Eq. (7)
  else
    Estimate $CCHI$ by the controller Eq. (6)
  end if
  Uniformly schedule next beacon dissemination time based on estimated $CCHI$;
end for

VANET are based on the IEEE 802.11p standard, as listed in Table I. The IDM parameters used in our experiments are given as follows: $L_0 = 3m$, $s_0 = 2m$, $a = 2m/s^2$, $b = 5m/s^2$, $T_0 = 1s$, $v_0 = 30m/s$.

TABLE I
802.11P PARAMETER SETTING

Parameter	Value	Parameter	Value
Channel data rate	18Mbps	Slot time	13 μs
SIFS	32 μs	AIFS	71 μs
Preamble length	32 μs	Plcp duration	8 μs
Propagation delay	2 μs	CWmin	15
Beacon frequency	0.1 s	Beacon priority	3
Beacon size	200 bytes	Target BRR	0.8

We evaluate the system performance of DBDCS in typical disturbance scenarios, where all vehicles experience two adjacent disturbance. For each disturbance, vehicles first decelerate from stable velocity $v_{stb} = 25$ m/s to lower velocity $v_{low} = 5$ m/s, and then maintain this speed for a period of time before accelerating to the original speed. The controller parameters are set as follows: $B_T = 0.8, K_a = K_p = 10, \Delta_{CCHI} = 0.01, \alpha = 0.05$, the adjusted range of CCHI is [0.1, 0.9]. We then evaluate the system metric of simple moving average (SMA) BRR where the period of SMA is set to 5s. Three different CCHI control algorithms have been implemented with the transmission range $R = 400$ m.

The simulation results are illustrated in Fig. 2. We observe that SMA BRR changed drastically under the constant C-CHI=0.5 (the default value specified in IEEE 1609.4 standard). For other two proposed CCHI control algorithms, we observe that CCHI can be adaptively and quickly adjusted based on current local traffic conditions to maintain SMA BRR at about the target value 0.8. For example, in Fig. 2 part (b), CCHI starts to sharply ascend when local traffic flow encounters the deceleration phase of disturbance at the time $t \approx 110$ s and $t \approx 300$ s. In addition, CCHI can maintain

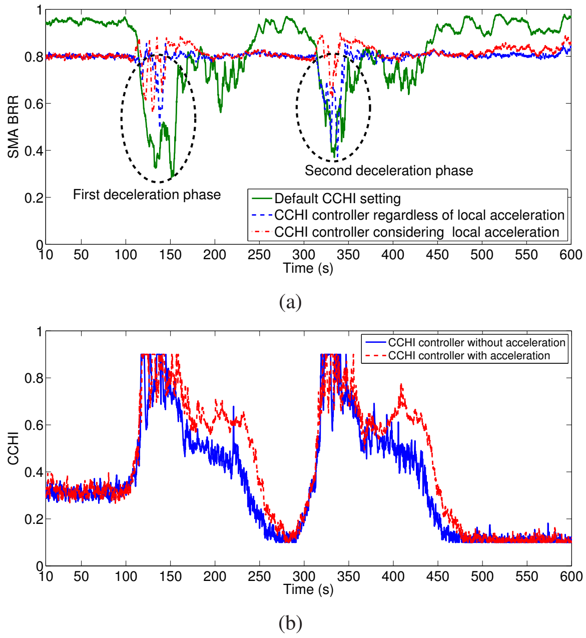

Fig. 2. System performance comparison under different CCHI control algorithms ($R = 400m$): (a) SMA BRR vs. time (b) CCHI vs. time.

approximately constant value in stable traffic flow, which indicates the stability of the proposed DBDCS.

Furthermore, if we compare the system performance under the two different control algorithms, the one considering local acceleration (the dash-dotted line in figure) and the one regardless of local acceleration (the dash line), we can easily observe that the former outperforms the latter specifically during two deceleration phases of the disturbances. For example, during the second deceleration phase, the lowest SMA BRR is about 0.65 for the former, yet for the latter the lowest SMA BRR is just around 0.4. Therefore, the simulation results validate the effectiveness of the proposed control algorithm of Eq. (7).

IV. CONCLUSIONS

In this paper, we have investigated the beacon dissemination in drastic disturbance scenarios. We proposed the DBDCS from the cyber-physical system perspective in which CCHI duration is dynamically adjusted based on the joint consideration of the vehicle dynamics and VANET behaviors. Numerical results show the efficiency of DBDCS especially in disturbance scenarios.

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