Transportation Research Part C 40 (2014) 215–230

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

On the network connectivity of platoon-based vehicular cyber-physical systems

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ARTICLE INFO

Article history:
Received 1 May 2013
Received in revised form 10 September 2013
Accepted 25 October 2013

Keywords:
Vehicular ad hoc networking (VANET)
Platoon-based vehicular cyber-physical systems
Inter-platoon connectivity
Expected transmission delay

ABSTRACT

In the past few years, vehicular ad hoc networking (VANET) has attracted significant attention and many fundamental issues have been investigated, such as network connectivity, medium access control (MAC) mechanism, routing protocol, and quality of service (QoS). Nevertheless, most related work has been based on simplified assumptions on the underlying vehicle traffic dynamics, which has a tight interaction with VANET in practice. In this paper, we try to investigate VANET performance from the vehicular cyber-physical system (VCPS) perspective. Specifically, we consider VANET connectivity of platoon-based VCPSs where all vehicles drive in platoon-based patterns, which facilitate better traffic performance as well as information services. We first propose a novel architecture for platoon-based VCPSs, then we derive the vehicle distribution under platoon-based driving patterns on a highway. Based on the results, we further investigate inter-platoon connectivity in a bi-directional highway scenario and evaluate the expected time of safety message delivery among platoons, taking into account the effects of system parameters, such as traffic flow, velocity, platoon size and transmission range. Extensive simulations are conducted which validate the accuracy of our analysis. This study will be helpful to understand the behavior of VCPSs, and will be helpful to improve vehicle platoon design and deployment.

1. Introduction

Vehicular ad hoc networking (VANET) is a promising technique for future inter-vehicle communications. Vehicles driving under VANET environment can be regarded as a typical *vehicular cyber-physical system* (VCPS), which is characterized by the tight coupling between a vehicle's physical dynamics (mobility) and the computing and communications aspects of the vehicle (Fallah et al., 2010). In a typical VCPS, VANET communication plays a critical role in both vehicle safety applications and infotainment services. Therefore, a comprehensive study on VANET performance in various traffic[1] conditions is an essential topic for VCPS, including the performance of network connectivity, medium access control (MAC) mechanism, routing protocol, quality of service (QoS), etc.

In the past few years, a lot of studies have been conducted on aforementioned issues. For example, VANET connectivity has been extensively investigated in different highway scenarios (Yousefi et al., 2008; Sou and Tonguz, 2011; Wu, 2009; Neelakantan and Babu, 2013; Ng et al., 2011), among which some important probability distributions have been obtained. Optimization of the IEEE 802.11p MAC mechanism is another hot topic which has been discussed in terms of both contention-free based and contention-based approaches (Katrin and Elisabeth, 2009; Almalag et al., 2012; Han and Dianati, 2012;

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[1] In this paper, "traffic" is limited to the context of vehicle transportation.

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http://dx.doi.org/10.1016/j.trc.2013.10.006

Song et al., 2011; Park et al., 2012). To tackle the interaction between VANET performance and vehicle dynamics, the relationship of three fundamental issues: traffic flow, safety, and communications capacity, within a simple transportation system has been investigated in Nekoui (2010), which initiated a more comprehensive study combining transportation with communication fields and sought to address their mutual dependencies. A case study is illustrated in Fallah and Sengupta (2012), where a cooperative vehicle safety system is designed by a systematic CPS approach.

Nevertheless, from the perspective of physical process in the VCPSs, most previous work takes individual vehicles as the objects, seldom considering the behavior of a group of vehicles on the VCPS performance. In practice, some consecutive vehicles with close space on the same direction can naturally be grouped into a *platoon*, in which a non-leading vehicle maintains a small distance with the preceding one, as shown in Fig. 1. Platoon-based driving pattern in highway is regarded as a promising driving manner and has been verified to bring benefits in many ways (van Arem et al., 2006). First, since vehicles in the same platoon are much closer to each other, the road capacity can be increased and the traffic congestion may be decreased accordingly. Second, the platoon pattern can reduce the energy consumption and exhaust emissions considerably because the streamlining of vehicles in a platoon can minimize air drag. Third, steady platoon formation facilitates more efficient information dissemination and sharing among vehicles in the same platoon.

Although many platoon related issues have been studied in the past several decades, such as traffic performance optimization by managing and controlling platoon (Hall and Chin, 2005; Chen et al., 2006; Uchikawa et al., 2010; Pueboobpaphan, 2010), platoon control method called *cooperative adaptive cruise control* (CACC) (Pueboobpaphan, 2010) with the help of VANET, etc., there is still a lack of the analysis and evaluation of the impact of platoon-based driving pattern on the performance of VCPS. For instance, with a given traffic flow rate, excessive vehicles in a single platoon could lead to transmission delay and packet loss due to contention-based CSMA/CA access mechanism of IEEE 802.11p, which cannot guarantee stringent real-time delivery for some critical safety applications such as collision avoidance and platoon control. Moreover, inter-platoon spacing is enlarged in this case and would impair the VANET connectivity among consecutive platoons. On the other side, few vehicles in a single platoon would discount the benefits obtained by vehicle platooning. Finally, intra-platoon communication could be interfered by adjacent platoons because of the smaller inter-platoon spacing in practice.

To summarize, platoon-based driving pattern can reshape the whole traffic flow distribution, compared to the original individual driving pattern, which could significantly affect the VANET communication in the VCPSs. Therefore, it is critical to re-evaluate the communication performance of VANET under platoon-based driving pattern. To this end, in this paper, we first propose a novel architecture for *platoon-based VCPSs*, taking into consideration the tight interaction between platoon dynamics and VANET. Then we analyze the probability distribution of platoon-based traffic flow. Based on the result, we further investigate inter-platoon connectivity and calculate the expected transmission delay between adjacent platoons. Finally, we conduct extensive simulation studies to validate the analytical results, taking into account the effect of various system parameters, such as traffic flow, velocity, platoon size and transmission range. To the best of our knowledge, this is the first time to address the VANET connectivity of platoon-based VCPSs.

The organization of this paper is described as follows. In Section 2, we first review the related work, especially on VANET connectivity analysis and platoon dynamics in various traffic conditions. In Section 3, we propose a general platoon-based VCPS architecture, illustrate all modules of the architecture, then specify a particular one to be investigated. In Section 4, we derive analytical expression of inter-platoon spacing distribution and calculate the expected message transmission delay of inter-platoon. In Section 5, we conduct extensive simulation experiments to validate the theoretical analysis, before concluding the paper in Section 6.

2. Related work

In this section, we will first review related work on VANET connectivity. Next, we give a short overview of the platoon dynamics because it essentially reflects the physical process in VCPSs and plays a critical role on VANET performance. Finally, we highlight our contributions by comparing our work with existing ones.

2.1. VANET connectivity

VANET connectivity is the fundamental issue regarding VANET performance and some important probability distributions have been obtained in the literature. In Yousefi et al. (2008), the authors investigated connectivity between vehicles in a sparse traffic condition where the number of vehicles passing the observer point is assumed to follow a Poisson process

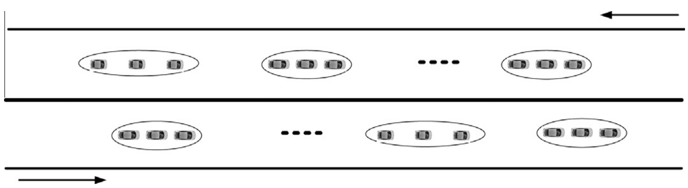

Fig. 1. Platoon-based driving pattern on a highway.