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Analytical model for information flow propagation wave under an information relay control strategy in a congested vehicle-to-vehicle communication environment

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ABSTRACT

Vehicular traffic congestion in a vehicle-to-vehicle (V2V) communication environment can lead to congestion effects for information flow propagation. Such congestion effects can impact whether a specific information packet of interest can reach a desired location, and if so, in a timely manner to influence the traffic system performance. Motivated by the usefulness and timeliness of information propagation, this paper aims to characterize the information flow propagation wave (IFPW) for an information packet in a congested V2V communication environment under an information relay control strategy. This strategy seeks to exclude information that is dated in the communication buffer under a first-in, first-out queue discipline, from being relayed if the information flow regime is congested. It trades off the need to enable the dissemination of every information packet as far as possible, against the congestion effects that accrue because of the presence of multiple information packets. A macroscopic two-layer model is proposed to characterize the IFPW. The upper layer is formulated as integro-differential equations to characterize the information dissemination in space and time under this control strategy. The lower layer adopts the Lighthill-Whitham-Richards model to capture the traffic flow dynamics. Based on the upper layer model, a necessary condition is derived which quantifies the expected time length that needs to be reserved for broadcasting the information packet of interest so as to ensure the formation of an IFPW under a given density of V2V-equipped vehicles. When the necessary condition is satisfied under homogeneous conditions, it is shown that the information packet can be propagated at an asymptotic speed whose value can be derived analytically. Besides, under the proposed control strategy, only a proportion of vehicles (labeled asymptotic density of informed vehicles) can receive the specific information packet, which can be estimated by solving a nonlinear equation. The asymptotic IFPW speed, the asymptotic density of informed vehicles, and the necessary condition for the IFPW, help in evaluating the timeliness of information propagation and the influence of traffic dynamics on information propagation. In addition, the proposed model can be used to numerically estimate the IFPW speed for heterogeneous conditions, which can aid in the design of traffic management strategies built upon the timely propagation of information through V2V communication.

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1. Introduction

Over the past few decades, dynamic traffic assignment models have sought to address how information affects traffic flow (e.g., Mahmassani and Peeta, 1995; Peeta and Yu, 2002; Paz and Peeta, 2009). In the context of vehicle-to-vehicle (V2V) communication, we seek to address how traffic flow impacts information propagation so as to develop a new generation of information dissemination strategies that can ensure that information reaches a desired location at specific time in order to achieve systemwide or individual level objectives for the V2V-based traffic system.

Connectivity in a V2V-based traffic system can be enabled by two types of communication: periodic and event-driven. Information broadcast by either type of communication is sealed into an information packet. Periodic communication using an information packet, often labeled beacon message, is used to proactively broadcast a vehicle's position, speed, heading, brake status, and other data to all neighboring vehicles. Such information can be of critical importance to the "receiver" vehicles; for example, it can enable the detection of an unsafe road condition. A beacon message is characterized by its short lifetime that spans only one hop or a few hops of broadcasting communication, with a high frequency of up to 10 times per second. Hence, beacon messages are appropriate for communicating with the local neighbors of the "sender" vehicle, and can be leveraged to alert drivers of potential collisions and hazards by providing up-to-date status information (Yang et al., 2004; Yeo et al., 2010; Talebpour et al., 2014).

Event-driven communication is triggered by a specific event, such as accident, sudden brake, or congestion, etc. It is useful for warning vehicles to approach the affected area with caution or adopt an alternate route to their destinations (Ding et al., 2010). It requires the multi-hop dissemination of an information packet that contains information related to the event (such as congestion or route guidance). The information packet released by the sender can be relayed by other vehicles inside and outside the initial sender's communication range, depending on the traffic characteristics and dynamics. Therefore, vehicles store the received information packet in their communication buffers and retransmit it to other vehicles. Since traffic safety and efficiency related applications have requirements related to information coverage and latency, it is critical to understand how information propagates in space and time in a V2V-based traffic system. This study considers the event-driven communication context, where multiple information packets, triggered by different events, are propagated simultaneously through multi-hop dissemination.

Modeling the information flow propagation through a multi-hop dissemination mechanism is challenging for a V2V-based traffic system, because the following characteristics need to be modeled appropriately. First, factors in both the information flow regime (such as information packet generation rate, communication frequency, and communication buffer size) and the traffic flow regime (such as traffic speed and density) significantly affect the characteristics of information flow propagation (Kim and Peeta, 2016, 2017; Kim et al., 2017a,b; Du and Dao, 2015; Du et al., 2016). The density of information flow changes with the traffic dynamics. In addition, due to limited channel capacity, the large number of information packets generated by multiple vehicles in a small space and a short time period can lead to congestion in the information flow regime, even if the traffic flow regime is not congested. For example, information flow congestion can exhibit trailing effects even if the traffic flow congestion dissipates. Second, congested information flow can cause a high degree of mutual interference among the transmitted signals. Any information packet that propagates to other vehicles in the vicinity of a vehicle is subject to signal attenuation over distance and interference imposed by other signals transmitted from surrounding vehicles. Third, a simple broadcasting protocol can lead to an exponential growth of retransmitted messages that congest a network, referred to as a broadcast storm (Tseng et al., 2002; Karagiannis et al., 2011). This phenomenon can cause packet collisions, implying that neither can the information stored in the communication buffer be disseminated nor can other information packets be stored into this buffer. Therefore, the multi-hop dissemination requires a special information relay control strategy to prevent packet collisions, so that information packets can share the limited channel capacity efficiently.

Past studies have addressed specific aspects of information flow propagation, including expected information propagation distance (Jin and Recker, 2006; Wang, 2007; Wang et al., 2010, 2011, 2012; Yin et al., 2013; Wang et al., 2015), connectivity of inter-vehicle communication (Jin and Recker, 2006; Ukkusuri and Du, 2008; Jin and Recker, 2010), and throughput of information packets to be transmitted to a given distance (Chen et al., 2010). However, all of these analytical studies are based on the assumption of instantaneous spatial propagation of information; that is, they do not consider the time dimension. They simply assume that the vehicles' locations are known based on some space headway distribution. Thereby, these approaches lack realism as they do not consider the impact of traffic flow dynamics on information propagation. Further, most of these analytical approaches oversimplify the wireless communication constraints (e.g., communication range, communication frequency, channel capacity, signal interference, etc.). Therefore, while the assumption of instantaneous information propagation can be analytically convenient, it has limitations in characterizing information flow propagation in the real world.

To facilitate the analysis of information propagation characteristics and the impacts of traffic dynamics at an aggregate level, Kim et al. (2015) introduce the concept of an information flow propagation wave (IFPW). When an information packet is generated in a V2V-based traffic system, it spreads through the relay process of multi-hop communications. From a macroscopic perspective, an IFPW "front" forms a moving boundary that separates the traffic flow into informed and uninformed regions, and moves towards the uninformed region (Kim et al., 2017a). This IFPW can be characterized by the direction and speed of the moving boundary. The quantification of speed and position of the IFPW front provides the macroscopic char-