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Information-traffic coupled cell transmission model for information spreading dynamics over vehicular ad hoc network on road segments

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ABSTRACT

Vehicular Ad Hoc Network (VANET) makes real-time traffic information accessible to vehicles en routes, thus possesses a great potential to improve traffic safety and mobility in the near future. Existing literature shows that we are still lack of approaches to track information spreading dynamics via VANET, which will prevent the potential applications from success. Motivated by this view, this research develops an information-traffic coupled cell transmission model (IT-CTM) to capture information spreading dynamics via VANET. More exactly, this study considers information spreading over a road segment forms a wave with a front and tail, each of which goes through the road segment following an intermittent transmission pattern due to traffic flow dynamics. The approach of IT-CTM discretizes a road segment into a number of cells. Each cell covers several intermittent transmissions. Mathematical methods are developed to capture the inner-cell and inter-cell movements of information front and tail, which enable us to track the information spreading dynamics along cells. Numerical experiments based on simulation and field data indicate that the IT-CTM can closely track the dynamic movements of information front and tail as well as the dynamic information coverage as a single or multiple piece(s) of information propagating via VANET on a one-way or two-way road segment. The mean absolute error (MAE) for tracking dynamic information coverage is <5% across all experiments in this study.

1. Introduction

Vehicular Ad Hoc Network (VANET) (also named as Vehicle-to-Vehicle (V2V) communication network or inter-vehicle communication network in the literature), enabling information exchange among vehicles through 5.9 GHz DSRC wireless communication (FCC, 1999), is a well-known technology, which possesses a great potential to improve traffic safety (Bai and Krishnan, 2006), mobility (Bauza et al., 2010) and environmental sustainability (Alsabaan et al., 2010; Tielert et al., 2010). The promising applications include real-time collision alerts, hazardous warning, coordinated driving, real-time navigation, traffic accident information warning, etc. Along with the development of these applications, it has been recognized that information availability plays a critical role to achieve the promise. For example, the application of real-time forward collision warning needs to know how fast information can reach target vehicles; spreading accident warning through VANET needs to have the knowledge about the information coverage in a local transportation network before the information

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expires. Accordingly, extensive research has been motivated to investigate information propagation in VANET from different perspectives. While wireless communication community mainly focused on designing communication protocols (Biswas et al., 2006; Dar et al., 2010), privacy protection (Burmester et al., 2008), safety (Nekovee, 2006), routing protocols (Chen et al., 2009; Taleb et al., 2007), etc., transportation community seeks to capture information propagation characteristics (such as connectivity, transmission distance, time delay, and coverage) in VANET associated with traffic stream features. This study shares the common interests of the latter, thus mainly reviews previous research in transportation community. Along with the review, we also differentiate and highlight the main contributions of this study.

First of all, many studies have explored instantaneous information propagation in VANET. The investigated topics include communication opportunity, instantaneous propagation distance, speed, and connectivity. The representative literatures are briefly discussed below. Jin and Recker (2006) computed the probability of a successful instantaneous information transmission between two vehicles in uniform and general traffic streams. Both Ukkusuri and Du (2008) and Jin and Recker (2010) developed analytical formulations to estimate the multi-hop connectivity of inter-vehicle communication network assuming stationary traffic stream, but different mathematical models are used. Wang (2007) developed mathematical formulas to provide the mean and variance of instantaneous information propagation distance as well as its distribution in VANET, considering the presence of equipped vehicles follows an independent homogeneous Poisson process. Wang et al. (2010) revisited this problem and made their approach adaptive to vehicle headway following a general distribution. Furthermore, Wang et al. (2012) and Yin et al. (2013) developed mathematical methods to estimate the expectation, variance, and probability distribution of instantaneous information propagation distance on parallel roads, assuming that vehicles' headway follows Gamma, Poisson, or Log-normal distribution. Clearly, this group of research studies information propagation at a snapshot under static traffic flow, since information propagation via wireless communication is much faster (in order of millisecond) than traffic flow variation (in order of minutes). Accordingly, the effect of traffic dynamics on information spreading is not fully considered.

Other literatures studied intermittent information propagation via VANET. Namely, information alternatively propagates through wireless communication or by vehicle carrying as wireless communication is not available. In what follows, we discuss some representative work. Artimy et al. (2005a, 2005b, 2006) examined the connectivity of VANET with static or dynamic assigned transmission range considering traffic flow dynamics. Schönhof et al. (2006) investigated how smart vehicle density impacts information propagation speed and efficiency considering dynamic communication link in a dynamic traffic flow on a two-way freeway traffic stream. Agarwal et al. (2008) studied the delay tolerant message propagation in VANET and developed the upper and lower bounds for information propagation speed as the functions of traffic density, vehicle speed, and transmission range. Wu et al. (2009) indicated that information propagation distance and speed depend on relative vehicle movement and other traffic characteristics such as vehicle density and average vehicle speed; Wang et al. (2014) proposed an analytical model to estimate the expected information propagation speed in a traffic flow with low smart vehicle penetration. Both instantaneous and carrier transmissions are considered. Du and Ukkusuri (2010) modeled intermittent information connectivity over a VANET on a one-way road segment by a time-expanded network, and then provided a closed-form formulation to estimate the average network connectivity (reachability) over a time period. Du and Dao (2015) provided the closed-form formulations to estimate the expected time delay by which a piece of information goes through a one-way or two-way road segments following intermittent information propagation via VANET. Kim et al. (2014) proposed an integrated model consisting of integro-differential equations to describe the information flow propagation mechanism and a partial differential equation to describe the traffic flow dynamics. The proposed approach provides a closed-form solution for the speed of the information flow propagation front. Overall, this group of research has made great contributions to understand the information propagation speed, distance, and time delay via VANET, considering various traffic conditions and necessary communication constraints. However, few existing solutions are able to track the information spreading dynamics via a VANET, while this is the main focus of the proposed study.

A few recent studies considered the information coverage via VANET over a local network. For example, by utilizing the information propagation model proposed in Wang (2007), Ng and Waller (2010) provided the lower and upper bounds of information propagation delay between two nodes in a network, where traffic flow characteristics are evaluated by a static traffic assignment model. Osman and Ishak (2015) developed a new measure of effectiveness to capture the connectivity robustness in a connected vehicle environment that accounts for traffic density, transmission range, and market penetration, which affect the robustness and stability of a connected vehicle environment.

The brief review above indicates two new research needs. First, even though existing solutions in literature provided various approximation methods to characterize information propagation, very few studies investigated the dynamic information spreading process via VANET, which is one of the most critical and unique features for VANET. Second, existing studies mainly considered a single piece of information, but in reality multiple pieces of information will propagate in the network simultaneously. We are still lack of the knowledge about the information merging or aggregation. This study seeks to partially make up the above gap.

The proposed approach considers that all vehicles on a road segment are equipped with wireless communication facilities; a piece of information, once initiated, flow through the road segment via a VANET formed by vehicles on this road. The spreading of a piece of information forms an information wave with a front and a tail. The movements of the information front and tail, which present the spreading of the information, follow an intermittent transmission pattern, which is significantly impacted by traffic flow dynamics. Specifically, the information front or tail may smoothly jump from one vehicle to another as two vehicles are well connected through wireless communication (i.e., instantaneous transmission), or they can