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Analysis of vehicular mobility in a dynamic free-flow highway

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ABSTRACT

The mobility model of vehicles under the time-varying vehicular speed assumption is quite challenging. However, vehicular movements are predictable as they are constrained by road or highway topology and layout. This paper presents an analytical model that mathematically investigates the vehicular movability in a single direction of a free-flow highway. The proposed model considers a strategy in which time is divided into intervals of equal length and each vehicle can change its speed at the beginning of each time slot. Full analytical derivation is provided for computing the conditional probability of number of vehicles and joint Poisson vehicular distribution accordingly. Moreover, the proposed model mathematically investigates the conditional expected number of vehicles and tail probability of the expected number of vehicles in a multi-lane highway. The accuracy of the analytical results is verified by simulation. The concluded results provide helpful insights towards designing new applications and improving performance of existing applications on vehicular ad hoc networks (VANETs).

1. Introduction

Vehicular ad hoc networks (VANETs) are one of the most interesting commercial applications of ad hoc networks. The growth in the variety of VANET applications and increased possibilities of vehicular dependent applications has gained much attention and attracted a great deal of interest from researchers in VANET communities. Vehicular communication is characterized by a dynamic environment but relatively predictable movability. Although vehicular mobility is constrained by road or highway topology and layout, modeling the movability in a VANET is quite involved; the movement of each vehicle is affected by many factors such as highway traffic situation, movements of neighboring vehicles, traffic signs, and driver's reactions to these factors [1–4]. Vehicles as mobile hosts can communicate with each other directly if and only if their Euclidean distance is not longer than the radio propagation range [5]. Each vehicle in this environment operates not only as a host but also as a router [6]. Utilizing dedicated short-range communications (DSRC) [7,8], enables a wide variety of driver-assisting applications such as vehicle-to-vehicle (V2V) communication and vehicle-to-roadside (V2R) messaging of traffic and accident information as well as allowing timely and intelligent communication to improve road safety and traffic stream [9–12]. Vehicles, due to their non-uniformity and different types have dissimilar movability patterns and adopt different speeds. This in turn results in variations in the density of a cluster, and the possibility of splitting or merging VANET connectivity [13,14].

Differences in mobility patterns and variation in vehicle speed in a VANET cause the traffic flow in each lane to vary dynamically. Because of the dynamic nature of vehicles in such a network, change from a densely connected to a sparsely disconnected environment may occur in a short time period [15]. As a result, the topology of the network changes frequently and vehicles come into intermittent contact with other vehicles traveling in other lanes in the same or opposite direction. These opportunistic contacts can be utilized to aid message propagation via multihop forwarding using intermediate nodes which overhear the message, regardless of being in a single lane or multiple lanes [16]. Networked environments that operate under such intermittent connectivity are also referred to as episodically connected, delay tolerant, or disruption tolerant networks (DTNs) [17]. Therefore, a DTN is essentially a store–carry–forward scheme, where a piece of information is cached or buffered in a node's memory when the network is disconnected.

In vehicular communication community, a cycle of information propagation process starts with physical movement of the vehicles as a catch-up process and ends with multihop transmission through connected vehicles as a forwarding process. Based on these two alternating processes information propagation cyclically renews in such DTNs [18]. In VANETs information propagation is directly affected by many factors such as highway situation, mov-

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ability pattern of adjacent vehicles, traffic flow, etc. Therefore, a comprehensive study in mobility tracking of vehicles can provide useful insights towards improving performance of existing applications and designing of new applications in vehicular communication aspects.

The main contributions of this paper are as follows:

- The proposed model provides a comprehensive spatiotemporal vehicular movability analysis and mathematically investigates the mobility model of vehicles traveling in single direction of a multilane highway.
- A synchronized random walk movability model is considered in which time is equally slotted. At any time interval the spatial distribution of the vehicles on the road follows a homogeneous Poisson process with intensity ρ.
- The conditional probability of number of vehicles, joint Poisson vehicular distribution, conditional expected number of vehicles and tail probability of the expected number of vehicles in a multi-lane free-flow highway are modeled mathematically.

The rest of this paper is organized as follows: In section 2 we summarize the related works and show vehicular mobility models. Section 3 describes the motivation. Section 4 presents the system model, describes some definitions, and presents the network architecture. Our analytical model is given in section 5. We evaluate the proposed model by extensive simulations in section 6. Finally, section 7 concludes this paper.

2. Related work

In [19], analytical results on the exponential distribution of intervehicle distance in a 1-D VANET were provided under different constant-speed model and Poisson arrival model. The authors showed that the number of vehicles passing an observation point on the road during any time interval follows a homogeneous Poisson process with an intensity of λ. They introduced an equivalent $M/D/\infty$ queuing model that studied the busy period in queuing theory. They claimed that multiple lanes can be neglected in their model because the difference between the coverage range of the devices and the distance between lanes is negligible. In [14], the information propagation speed (IPS) in a 1-D VANET was studied in which vehicles are Poisson distributed and moved at the same speed but in the opposite directions. The authors derived the upper and lower bounds, which provided a hint on the impact of vehicle density on the IPS. In [20], Wu et al. considered a 1-D VANET where vehicles are Poisson distributed and the vehicle speeds are uniformly distributed in a designated range. They showed that the message propagation process can be modeled as a renewal reward process in which message propagation cyclically alternates between catch-up and forward processes. In our earlier work [18], we mathematically formulated the average IPS based on the number of renewal cycles that a piece of information needs to be delivered. We considered a time-varying vehicular speed model in which vehicles are Poisson distributed and travel in the same lane or different lanes but in the same direction. Like [20], we assumed that a cycle of information propagation starts with physical movement of the vehicles as a catch-up process and ends with multihop transmission through connected vehicles as a forwarding process. Baccelli et al. in [21] provided a full analysis of the information propagation process in bidirectional vehicular delay tolerant networks such as roads or highways. They proved that under a certain traffic intensity threshold, on average, information propagates at the vehicle speed. Above this threshold, in a situation where vehicles are connected in an obtained cluster, information propagates much faster. They considered a bidirectional vehicular network, such as a highway, where vehicles move in opposite directions at constant speed v. In [22], the authors demonstrated that, under free flow traffic, the number of connected vehicles increases as either the vehicle density or the number of lanes grows. They found that the intervehicle distances had a major impact on connectivity when it is within 3–4 times larger than the radio range. Beyond this distance, the connectivity declines slowly. Zhang et al. in [13,23] considered a model in which time is divided into intervals of equal length and each vehicle changes its speed at the beginning of each time slot, independent of its speed in other time slots.

In our earlier work [24], we considered a time-varying vehicular speed assumption that allowed vehicles to change their speed independent of the other vehicles as well as the other time intervals. We proposed an analytical model for calculating the probability density function (pdf) of connectivity.

In this paper, a comprehensive analysis for investigation of the joint Poisson distribution in a single direction of multilane highway is mathematically proposed. We provide a synchronized random walk movability model in which time is equally slotted. At any time interval the spatial distribution of the vehicles on the road follows a homogeneous Poisson process with intensity ρ. Using these considerations, we study the mobility tracking of vehicles traveling in a single direction of a free-flow highway and evaluate the impact of vehicular densities and speed distributions of dynamic vehicles in different lanes.

3. Motivation

In the context of vehicular networks, many previous studies use the simplistic assumption of mesoscopic mobility in which vehicle speeds are equal at all times [14,21,25]. Mesoscopic mobility model is used to model the static mobility in which the intervehicle distances and communication links are stable and vehicles follow the traffic in a dense situation or move independently at a maximum speed in a sparse situation while traveling in a road or highway [26].

On the other hand, vehicles, due to their non-uniform and different types have dissimilar movability patterns and adopt different speeds (i.e. the microscopic mobility model). In other words the movement of each vehicle in the VANET is affected by many factors such as highway situation, movement of neighbors, information on the messaging signs along the highway, road signs, traffic lights and driver's reactions to these factors [2,26].

Only a few studies provided a dynamic mobility pattern by which vehicles could utilize variable speed [13,23]. This work tries to analyze and address the dynamic vehicular mobility aspects in a single direction of a multi-lane highway. In order to provide more a realistic movability analysis, the proposed model considers a synchronized random walk model and mathematically investigates the microscopic mobility model of vehicles traveling in different lanes in a free-flow highway with a time-varying traffic flow assumption.

The broadcast nature of the wireless medium can be advantageous to support multi-path capabilities that information-centric networking (ICN) can enable for transport of information in VANETs [27]. Mobile and wireless communications as well as mobile cloud computing are a profoundly important technology that is rapidly growing and continuously changing human life [28]. The taxonomy of cloud-based vehicular networks is addressed from the standpoint of the service relationship between cloud computing and VANETs [29]. It is extremely necessary to efficiently provide comprehensive study for future vehicular networks especially cloud-based VANETs.