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Mobility analysis in vehicular ad hoc network (VANET)

Liren Zhang *, Abderrahmane Lakas, Hesham El-Sayed, Ezedin Barka

College of Information Technology, United Arab Emirates University, Al-Ain, UAE

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ABSTRACT

This paper focuses on vehicle mobility analysis in VANET. The performance of vehicle mobility in terms of average inter-vehicle link available time and the average number of inter-vehicle link changes for maintaining an active link in VANET is analyzed using both handover model and random moving model, respectively. The theoretical analysis is verified by simulation experiments. The numerical results indicate that the analytical random moving model is able to appropriately present the behavior of vehicle moving under different conditions, especially when mobile vehicle is moving relatively fast. On the other hand, the effect of traffic conditions on the accuracy of theoretical analysis is also investigated.

1. Introduction

In a vehicular ad hoc network (VANET) without pre-existing fixed infrastructure, end-to-end multi-hop communications are based on packet relay through mobile vehicles, which are acting as routers. Since mobile vehicles are free to move randomly, vehicle mobility is one of the most important issues in protocol design. The effects of vehicle mobility on traffic flow control, routing path selection, mobile channel assigning, control overhead estimation and QoS management have been concerned by many researchers (McDonald and Znati, 1999; Santi and Blough, 2003; Stojmenovic, 2002; Chiang, 1998; Johansson et al., 1999; Bettstetter, 2001; Haas, 1997; Hong et al., 1999; Wang and Baochun, 2002; Garcia and Madrga, 1999; Das et al., 2001; Shen and Du, 2010; Kim et al., 2009; Aschenbrucka et al., 2011; Ahmed et al., 2010; Zaidi and Mark, 2011), in which a common approach for performance analysis in such networks is the synthetic mobility model on geographical basis by either simulations or realistic vehicular trace data obtained by street measurements (Fan Li and Wang, 2007).

However, most of these models are limited to a specific road traffic conditions such as street conditions, urban conditions, traffic conditions and vehicle density.

Mobility models usually focus on the individual moving behavior between mobility epochs. Here, an epoch is considered as short time period, in which both moving speed and moving direction of vehicles are approximately considered as constant. One popular mobility model is the random moving mobility model (Camp et al., 2002), (McDonald and Znati, 1999), (Garcia and Madrga, 1999), (Nanda, 1993), in which the moving of vehicle is divided into a sequence of mobility epochs. In this model, both of the speed and direction are constant within an epoch, but randomly vary from epoch to epoch. Another mobility model being widely used is called random waypoint model (Johansson et al., 1999; Das et al., 2001; Bettstetter et al., 2003; Navidi and Camp, 2004; Fan Li and Wang, 2007), which is an extended version of random moving model. In the random waypoint model, the entire movement of a vehicle is divided into repeating pause and motion periods. The mobile vehicle stays at a position for a random period and then moves to a new randomly selected position at a constant speed that is assumed to be uniformly distributed. Nadeem et al. (2004) modified the random waypoint model by accepting road length, average speed, number of lanes, and average gap between vehicles as parameters. Saha and Johnson (2004) first attempted to propose a realistic street mobility model, where they used the road information from the TIGER (*Topologically Integrated Geographic Encoding and Referencing*) (US Census Bureau) US road map by US Census Bureau. In their model, they convert the map into a graph. Then they assume that each node starts at some random point on a road segment and moves toward a random destination following shortest path algorithm.

A new trend of building mobility model is using the realistic vehicular trace data. Füßler et al. (2005) used a set of movement traces derived from typical situations on German Autobahns to simulate the traffic movement on a highway. The movement of cars is defined as tuples of a one-dimensional position and a lane on the highway for discrete time steps of 0:5 s. They cut those movement trace data into valid portions and combine them into certain movement scenarios. Jetcheva et al. (2003) recorded the movement traces of the buses of the public transportation system in Seattle, Washington. However, these traces only describe the

* Corresponding author. Tel.: +971 37135611.
E-mail address: lzhang@uaeu.ac.ae (L. Zhang).

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movement of the buses; they represent a tiny fraction of the total number of road traffic participants. Recently, Naumov et al. (2006) introduced a new source of realistic mobility traces for simulation of inter-vehicle networks. Their traces are obtained from a *Multi-agent Microscopic Traffic Simulator* (MMTS) (Zaidi and Mark, 2011), which is capable of simulating public and private traffic over real regional road maps of Switzerland with a high level of realism. Other mobility models include the Markovian Model (Chiang, 1998), the Incremental Model (Haas, 1997), the Smooth Model (Bettstetter, 2001), and group mobility models, such as the Reference Point Group Mobility Model (Hong et al., 1999) and the Reference Velocity Group Mobility Model (Wang and Baochun, 2002). Technical reviews on the existing mobility models are presented in Camp et al. (2002) and Hong et al. (1999).

Since the analysis of random moving behaviors of mobile vehicles is complicated, the most researchers currently (Stojmenovic, 2002; Chiang, 1998; Johansson et al., 1999; Bettstetter, 2001; Haas, 1997; Hong et al., 1999; Wang and Baochun, 2002; Garcia and Madrga, 1999; Das et al., 2001) use simulation as the major tool to evaluate the performance of VANET. Where, vehicle mobility in a simulation takes into account the probability distribution functions covering both moving direction and speed continuously as the simulation progresses. However, such simulation usually requires huge amount of computation power to achieve the statistics of steady-state performance. Hence, study of characteristics of vehicle mobility and their effects on VANET with large amount of mobile vehicles intend is usually impractical by simulation rather than analytical methodology. However, so far a few of research works have studied the vehicle mobility using analytical methods. McDonald and Znati (1999) theoretically described the aggregate behavior of mobile vehicle including the characteristics of the aggregate distance and direction using a random mobility vector, which is assumed to follow a Rayleigh distribution. In their paper, mobile vehicle are dynamically divided into clusters and the impact of mobility is presented in terms of link availability. Moreover, the stationary distributions of location, speed and pause time for the random waypoint mobility model have been derived in Bettstetter et al. (2003) and Navidi and Camp (2004). These analytical results can be applied to design efficient and reliable simulations.

The impact of vehicle mobility can be measured in terms of inter-vehicle link available time and number of inter-vehicle link changes to maintain an active connectivity in VANET (Hong and Rappaport, 1986). The link available time is defined as the time of a wireless link between an arbitrary pair of neighboring vehicles, which represents the time period that the moving vehicles can schedule wireless medium access for next handoff, assign the rate of sending "Hello" packets to the neighboring vehicles, and update location information. Another important parameter is the number of inter-vehicle link changes to maintain active connectivity. This is because that outage of inter-vehicle link can trigger new route discover/recovery process. For the purpose of alleviating control overheads, maintaining short end-to-end delay and utilizing the network resource efficiently, the number of link changes must be as little as possible. To the best of our knowledge, there are no existing reports of theoretical analysis to derive these two mobility parameters in VANET.

In this paper, the random movement of mobile vehicle is characterized by the relative velocity between two neighboring vehicles. The performance analysis focuses on the mobility characteristics using handover model (Hong and Rappaport, 1986) and random moving model, respectively. The first major contribution of this paper is the probability distribution functions of mobile vehicle mobility in terms of inter-vehicle link available time and number of inter-vehicle link changes to maintain an active connectivity, which are the most important parameters able to represent the vehicle mobility behavior in VANET (Camp et al., 2002; McDonald and Znati, 1999; (Garcia and Madrga, 1999; Nanda, 1993). The second major contribution is a novel methodology for the analysis using the random moving model. Since the random moving model has been considered as the best model to describe the real-time moving behavior of vehicle mobility so far, the analytical methodology presented in this paper is able to be extended into the other complicated mobility models.

2. Vehicle mobility model

The vehicle mobility modeling presented in this paper is a discrete-time process that characterizes the movement of mobile vehicle in a two-dimensional space. The instantaneous movement of two neighboring vehicle h_i and h_j can be represented by velocity v_j and v_i, respectively, where h_i is denoted as the reference point with a radio transmission range of radius r, while h_j is moving within the transmission range of h_i. The instantaneous velocity difference between h_i and h_j is represented using a relative velocity $v_d = v_j - v_d$. We assume that both $|v_j|$ and $|v_j|$ are in a range of $(0,V_m)$ with a general distribution, where V_m is the maximum value, then the absolute value of relative velocity $|v_d|$ is obviously in the range of $(0,2V_m)$.

Fig. 1 illustrates that vehicle h_j moves through the radio coverage area of a sequence of conjoint vehicle h_i $(i=1,2,3,\ldots)$ to maintain its active connectivity in VANET. The inter-vehicle link available time between h_j and h_i is defined as the sojourn time T_i $(i=1,2,3,\ldots)$, which is the time that h_j moves in the inside of the radio coverage boundary of h_i. However, as shown in Fig. 2, vehicle h_j may not be able to find any other neighboring vehicle to maintain its active connectivity in the VANET for a short period of time, when h_j moves out the radio coverage boundary of h_i. In the paper, our analysis is done under an assumption that a sequence of conjoint vehicle h_i $(i=1,2,3,\ldots)$ is always available for vehicle h_j to maintain its active connectivity in VANET, as shown in Fig. 1. However, the numerical results obtained from analytical models are validated by simulations which take into account of link outages due to temperately not available of conjoint vehicle to maintain an active link in VANET, as shown in Fig. 2.

Consider an arbitrary active connectivity of negative exponential distribution holding time with a mean value of $1/\mu_C$. Let N_{hc} be the number of inter-vehicle link changes to maintain the active connectivity during the holding time. As shown in Fig. 1, vehicle h_j has an established link connection with vehicle h_1 in the time interval T_1. When h_j moves out of the radio coverage range of h_1 at the end of time interval T_1, h_j must switch its link connectivity to neighboring vehicle h_2 immediately at the beginning of the time interval T_2. If the radio coverage range of conjoint vehicle $h_i (i = 1,2,\cdots)$ are overlapped each other, then h_j is able to

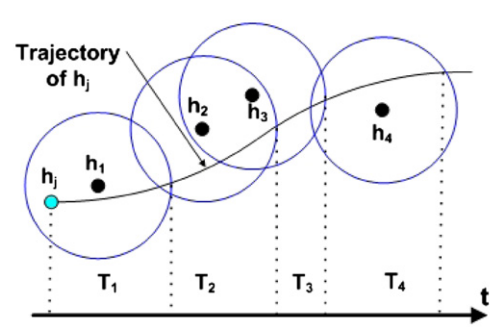

Fig. 1. The sojourn time for h_j traveling in the network.

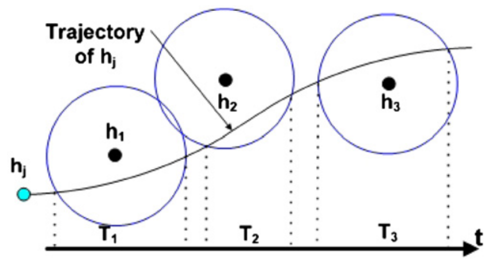

Fig. 2. The sojourn time for h_j.

continually switch its link from h_i to h_{i+1} at the end of sojourn time T_i $(i=1,2,3,\ldots)$.

Let $f_{T_i}(t)$ be the PDF (probability density function) of T_i, then the Laplace transform of $f_{T_i}(t)$ is given by

$$f^*_{T_i}(s)=\int_{-\infty}^{\infty} f_{T_i}(t)e^{-st}dt$$

Since the holding time is negative exponentially distributed, the PDF of holding time is given by

$$f_H(t)=\mu_C e^{-\mu_C t} \quad (t>0),$$

where $1/\mu_C$ is the average holding time. Therefore,

$$f^*_{T_i}(\mu_C)=\int_{-\infty}^{\infty} f_{T_i}(t)e^{-\mu_C t}dt=E(e^{-\mu_C t}) \tag{1}$$

As shown in Fig. 1, to maintain an active connection, the average number of inter-vehicle link changes experienced by h_j can be obtained by:

$$E(N_{hc}|_{T_1,T_2,T_3,\ldots})=1\int_0^{T_1}\mu_C e^{-\mu_C t}dt+2\int_{T_1}^{T_2}\mu_C e^{-\mu_C t}dt +3\int_{T_2}^{T_3}\mu_C e^{-\mu_C t}dt+\cdots \tag{2}$$

where the term $\int_0^{T_1}\mu_C e^{-\mu_C t}dt$ represents the first handover experienced by h_j during the time interval $[0,T_1]$, the term $\int_{T_1}^{T_2}\mu_C e^{-\mu_C t}dt$ represents the second handover during the time interval $[T_1,T_2]$, and so on. Note that since the sojourn time T_1, T_2, $\cdots$, T_i,$\cdots$ represent the time that h_j moves in the inside of the radio coverage boundary of h_1, h_2, $\cdots$, h_i,$\cdots$, respectively. Note that the time interval $[0,T_1]$, $[T_1,T_2]$, $\cdots$, $[T_{i-1},T]_i$,$\cdots$ considered for handover are not unequal time intervals.

The average number of inter-vehicle link changes is defined as $E(N_{hc})=E(E(N_{hc}|_{T_1,T_2,\cdots,T_i,\ldots}))$ that can be obtained by combining Eqs. (1) and (2), that is

$$E(N_{hc})=f^*_{T_i}(\mu_C)+[f^*_{T_i}(\mu_C)]^2+[f^*_{T_i}(\mu_C)]^3+\cdots =\frac{f^*_{T_i}(\mu_C)}{1-f^*_{T_i}(\mu_C)} \tag{3}$$

3. Mobility analysis

In this section, effects of vehicle mobility in terms of average inter-vehicle link available time and average number of inter-vehicle link changes to maintain an active connectivity are analyzed using both mobile handover model (Hong and Rappaport, 1986) and random moving model (Camp et al., 2002; McDonald and Znati, 1999; Garcia and Madrga, 1999; Nanda, 1993), respectively.

3.1. Mobility analysis using mobile handover model

The mobile handover model (Hong and Rappaport, 1986) is analyzed with the following assumptions: (1) the relative moving rate and the relative moving direction between two mobile vehicles are considered as two independent random variables, (2) vehicle moving velocity only randomly changes when inter-vehicle link changes, and (3) vehicle moving rate has a general distribution and moving direction is uniform distribution ranging from 0 to2π (Navidi and Camp, 2004; Fan Li and Wang 2007).

3.1.1. Analysis of inter-vehicle link available time

Consider mobile vehicle h_j moves in the inside of the radio coverage boundary of mobile vehicle h_i for a sojourn time T_i at a constant relative velocity v_{d_i}. Let X_i denote the distance that h_i has traveled during the sojourn time T_i and $f_{v_d}(v)$ denote the probability density function (PDF) of v_{d_i}. The PDF of the distance X_i that h_j has traveled during the sojourn time T_i is given by (Hong and Rappaport, 1986), that is:

$$f_{X_i}(x)=\begin{cases}\frac{2}{\pi r^2}\sqrt{r^2-\left(\frac{x}{2}\right)^2}, & 0\le x\le 2r\\ 0 & \text{elsewhere}\end{cases} \tag{4}$$

where r is the radius of radio coverage of h_i. We assume that all mobile vehicles in the VANET have the same radio coverage range. Since the sojourn time T_i is given by $T_i=X_i/v_{d_i}$, its PDF can be obtained using Eq. (4), that is

$$f_{T_i}(t)=\int_{-\infty}^{\infty}|v_{d_i}|f_{X_i}(tv_{d_i})f_{v_d}(v_{d_i})dv_{d_i} =\int_0^{(2r/t)}\frac{2v_{d_i}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_i}}{2}\right)^2}f_{v_d}(v_{d_i})dv_{d_i},\quad t\ge 0 \tag{5}$$

The cumulated density function (CDF) for T_i is given by

$$F_{T_i}(t)=\int_0^t f_{T_i}(m)dm =\int_0^{(2r/t)}f_{v_d}(v_{d_i})\left[1-\frac{tv_{d_i}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_i}}{2}\right)^2}-\frac{2}{\pi}\arcsin\left(\frac{tv_{d_i}}{2r}\right)\right]dv_{d_i} \tag{6}$$

In order to separate the analytical result using mobile handover model from the result using mobile random moving model, which will be presented in the following subsection, we use a term $E(T_{X1})$ to represent the average inter-vehicle link available time between h_j and h_i for mobile handover model, which can be obtained as

$$E(T_{X1})=\int_0^{\infty}tf_{T_i}(t)dt =\int_0^{\infty}\int_0^{(2r/t)}\frac{2tv_{d_i}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_i}}{2}\right)^2}f_{v_d}(v_{d_i})dv_{d_i}dt =\frac{8r}{3\pi}E\left(\frac{1}{v_{d_i}}\right) \tag{7}$$

where $E(1/v_{d_i})$ is the expected mean value of $1/v_{d_i}$.

3.1.2. Analysis of average number of inter-vehicle link changes

Let $f^*_{T_{X1}}(s)$ be the Laplace transform function of $f_{T_{X1}}(t)$. The value of $f^*_{T_{X1}}(\mu_C)$ can be obtained as

$$f^*_{T_{X1}}(\mu_C)=\int_0^{\infty}f_{T_{X1}}(t)e^{-\mu_C t}dt =\frac{2}{\pi r^2}\int_0^{\infty}e^{-\mu_C t}\int_0^{(2r/t)}v_{d_i}f_{v_d}(v_{d_i})\sqrt{r^2-\left(\frac{tv_{d_i}}{2}\right)^2}dv_{d_i}dt \tag{8}$$

Recall Eq. (3), the average number of inter-vehicle link changes, denoted as $E(N_{hc1})$ for h_j to maintain an active connectivity in VANET under the mobile handover model (Hong and Rappaport, 1986) is given by

$$E(N_{hc1})=\frac{f^*_{T_{X1}}(\mu_C)}{1-f^*_{T_{X1}}(\mu_C)}, \tag{9}$$

where holding time T_C is assumed as negative exponential distribution with a mean value of $1/\mu_C$.

3.2. Mobility analysis using random moving model

In the following analysis, the relative vehicle velocity v_d is modeled as a discrete-time random variable, which is described by a new technical term. The sojourn time T_i, $(i=1,2,3,\ldots)$ during which h_j moves in the inside of the radio coverage boundary of h_i is divided into a sequence of v_d small time intervals, called Relative Epoch (RE), denoted as $RE_{1_i}, RE_{2_i}, \ldots, RE_{n_i}, \ldots RE_{N_i}$, so that the relative velocity v_d can be approximately considered as a constant within each individual RE, but v_d may change randomly at the beginning of each RE. That is, h_j moves into the radio coverage boundary of h_i at the beginning of RE_{1_i}, remains its inter-vehicle connection with h_i for consecutive (N_i-1) REs and switches its inter-vehicle connection to h_{i+1} during RE_{Ni}. In this case, the handover for h_j from h_i to h_{i+1} occurs during the RE_{N_i}.

3.2.1. Analysis of inter-vehicle link available time

Let T_{n_i} $(n\in\{1_i,2_i,\ldots,N_i-1\})$ be the duration of RE_{n_i}. Therefore, the total average inter-vehicle available time, denoted as $E(T_{X2})$, that the h_j moves in the inside of radio coverage boundary of h_i is given by

$$E(T_{X2}) = \sum_{n_i=1_i}^{(N-1)_i} E(T_{n_i}) + E\left(\tilde{T}_{N_i}\right) \tag{10}$$

where $E(\tilde{T}_{i_N})$ is the sojourn time that h_j remains its connection with h_i before switching to h_{i+1} during RE_{N_i}. Clearly, $\tilde{T}_{N_i} \le T_{N_i}$, where T_{N_i} is the sojourn time that h_j remains its connection with h_i for whole time interval RE_{N_i}.

First of all, we focus on deriving of the term $E(T_{N_i})$ in Eq. (10) by considering $T_{n_i}(n_i\in\{1_i,2_i,\ldots,(N_i-1)_i\})$, in which h_j moves a distance of X_{n_i} at a constant relative velocity v_{dni}. Recall Eq. (5), the probability density function (PDF) of T_{n_i} can be obtained as

$$f_{T_{n_i}}(t) = \int_0^{(2r/t)} \frac{2v_{d_{n_i}}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_{n_i}}}{2}\right)^2} f_{v_d}(v_{d_{n_i}})dv_{d_{n_i}}, \qquad t\ge 0. \tag{11}$$

Likewise, the average duration of T_{n_i} can be calculated by recalling Eq. (7), that is

$$\begin{aligned} E(T_{n_i}) &= \int_0^\infty t f_{T_{n_i}}(t)dt \\ &= \int_0^\infty \int_0^{(2r/t)} \frac{2tv_{d_{n_i}}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_{n_i}}}{2}\right)^2} f_{v_d}(v_{d_{n_i}}) \Bigg) dv_{d_{n_i}}dt \\ &= \frac{8r}{3\pi}E\left(\frac{1}{v_{d_{n_i}}}\right) \end{aligned} \tag{12}$$

Second, we focus on deriving of the term $E(\tilde{T}_{i_N})$ in Eq. (10). It is clear that h_j is able to move a distance of X_{N_i} at a constant relative velocity $v_{d_{N_i}}$ in RE_{N_i}, if the handover does not occur. However, h_j only moves a distance of $\tilde{X}_{i_N}$ remaining its connection with h_i during RE_{N_i} due to the handover from h_i to h_{i+1}. In this case, the probability density function of $\tilde{T}_{N_i}$ can be given by

$$f_{\tilde{X}_{N_i}}(t) = \begin{cases} \frac{f_{T_{N_i}}(t)}{F_{T_{N_i}}(E(T_{N_i}))}, & 0\le t\le \tilde{T}_{N_i} \\ 0 & \text{elsewhere} \end{cases} \tag{13}$$

In Eq. (13), the term $f_{T_{N_i}}(t)$ is the probability density function of T_{N_i} and the term $F_{T_{N_i}}(E(T_{N_i}))$ is the cumulated density function corresponding to the average sojourn time $E(T_{N_i})$ in RE_{N_i}, where term $f_{T_{N_i}}(t)$ and $E(T_{N_i})$ can be obtained from Eqs. (11) and (12), respectively. Recall Eq. (6), $F_{T_{i_N}}(E(T_{i_N}))$ can be obtained as

$$F_{T_{Ni}}(E(T_{Ni})) = \int_0^{(2r/E(T_{Ni}))} f_{v_d}(v_{d_{Ni}})\left[1-\frac{tv_{d_{Ni}}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_{Ni}}}{2}\right)^2} - \frac{2}{\pi}\arcsin\left(\frac{tv_{d_{Ni}}}{2r}\right)\right]dv_{d_{Ni}}, \tag{14}$$

Therefore, the expected mean value $E(\tilde{T}_{N_i})$ can be presented as

$$\begin{aligned} E(\tilde{T}_{N_i}) &= \int_0^\infty t f_{\tilde{T}_{N_i}}(t)dt \\ &= \frac{1}{F_{T_{N_i}}(E(T_{N_i}))}\int_0^{E(T_{N_i})}\int_0^{(2r/t)} \frac{2tv_{d_{N_i}}}{\pi r^2}\sqrt{r^2-\left(\frac{tv_{d_{N_i}}}{2}\right)^2} f_{v_d}(v_{d_{N_i}})dv_{d_{N_i}}dt \\ &= \frac{8}{3\pi F_{T_{N_i}}(E(T_{N_i}))}\left\{\frac{r}{v_{d_{N_i}}} - \frac{1}{r^2}\int_0^{(2r/E(T_{N_i}))}\frac{f_{v_d}(v_{d_{N_i}})}{v_{d_{N_i}}}\left[r^2-\left(\frac{E(T_{N_i})v_{d_{N_i}}}{2}\right)^2\right]^{(3/2)} dv_{d_{N_i}}\right\} \end{aligned} \tag{15}$$

3.2.2. Analysis of average number of inter-vehicle link changes

Consider that the overall sojourn time T_{X2} of h_j having active link with h_i under the random moving model is given by

$$T_{X2} = \sum_{n_i=1_i}^{(N_i-1)_i} T_{n_i} + \tilde{T}_{N_i}, \tag{16}$$

Therefore, the probability density function of the overall sojourn time T_{X2} that h_j is given by

$$f_{T_{X2}}(t) = \sum_{n_i=1_i}^{(N_i-1)_i} f_{T_{n_i}}(t) + f_{\tilde{T}_{N_i}}(t) \tag{17}$$

where term $f_{T_{n_i}}(t)$ is given by Eq. (11) and term $f_{\tilde{T}_{N_i}}(t)$ is given by Eq. (13).

Let $f^*_{T_{X2}}(s)$ be the Laplace transform function of $f_{T_{X2}}(t)$. Then, $f^*_{T_{X2}}(\mu_C)$ can be obtained using Eq. (13), that is

$$\begin{aligned} f^*_{T_{X2}}(\mu_C) &= \int_0^\infty f_{T_{X2}}(t)e^{-\mu_C t}dt \\ &= \int_0^\infty \left[\sum_{n_i=1_i}^{(N_i-1)_i} f_{T_{ni}}(t) + f_{\tilde{T}_{Ni}}(t)\right] e^{-\mu_C t}dt \\ &= \sum_{n_i=1_i}^{(N_i-1)_i}\int_0^\infty f_{T_{ni}}(t)e^{-\mu_C t}dt + \int_0^\infty f_{\tilde{T}_{Ni}}(t)e^{-\mu_C t}dt \end{aligned} \tag{18}$$

Recall Eq. (8), the term $\int_0^\infty f_{T_{ni}}(t)e^{-\mu_C t}dt$ can be calculated as

$$\int_0^\infty f_{T_{ni}}(t)e^{-\mu_C t}dt = \frac{2}{\pi r^2}\int_0^\infty e^{-\mu_C t}\int_0^{(2r/t)} v_{d_{ni}} f_{v_d}(v_{d_{ni}})\sqrt{r^2-\left(\frac{tv_{d_{ni}}}{2}\right)^2}dv_{d_{ni}}dt. \tag{19}$$

Likewise, the term $\int_0^\infty f_{\tilde{T}_{Ni}}(t)e^{-\mu_C t}dt$ can be calculated as

$$\int_0^\infty f_{\tilde{T}_{Ni}}(t)e^{-\mu_C t}dt = \frac{2}{\pi r^2}\int_0^\infty e^{-\mu_C t}\int_0^{(2r/t)} v_{d_{Ni}} f_{v_d}(v_{d_{Ni}})\sqrt{r^2-\left(\frac{tv_{d_{N_i}}}{2}\right)^2}dv_{d_{Ni}}dt \tag{20}$$

Recall Eq. (3), the average number of inter-vehicle link changes, denoted as $E(N_{hc2})$, for h_j to maintain an active connectivity during holding time period under random moving model is given by

$$E(N_{hc2}) = \frac{f^*_{T_{X2}}(\mu_C)}{1-f^*_{T_{X2}}(\mu_C)} \tag{21}$$

where term $f^*_{T_i}(\mu_C)$ is given by Eq. (17).

3.3. Numerical result and discussion

The numerical results are calculated under the condition that the vehicle moving velocity for both h_j and h_i, including the speed (v_i and v_j) and direction (θ_i and θ_j) are uniformly distribution in the ranges of $[0,V_m]$ and $[0,2\pi]$, respectively. Note that this condition is the same as being used in the simulations for performance analysis (Camp et al., 2002; Johansson et al., 1999).

Fig. 3 illustrates the effects of radio coverage r on the average inter-vehicle link available time versus maximum moving speed V_m, where $E(T_{X1})$ and $E(T_{X2})$ are calculated by equation for the mobile handover model and Eq. (10) for the random moving model, respectively. It can be seen that $E(T_{X2})$ is larger than $E(T_{X1})$. The reason is that for a pair of given values of r and V_m, the relative velocity under the random moving model is a discrete random variable, which is less than or equal to V_m. Comparing to the relative velocity in mobile handover model which is always equal to V_m. The comparison of Fig. 3(a) and (b) illustrates that $E(T_{X2})$ increases when the average RE duration decreases. By contrast, it can be observed that the difference between $E(T_{X1})$ and $E(T_{X2})$ increases when either r increases or V_m decreases. This indicates that the stability of inter-vehicle link can be approved by either increasing of the radio coverage or by decreasing of the vehicle speed. However, when RE duration is small enough, the corresponding moving velocity is varying more frequently, which means that the random moving model is able to describe vehicle mobility characteristics better that the handover model does.

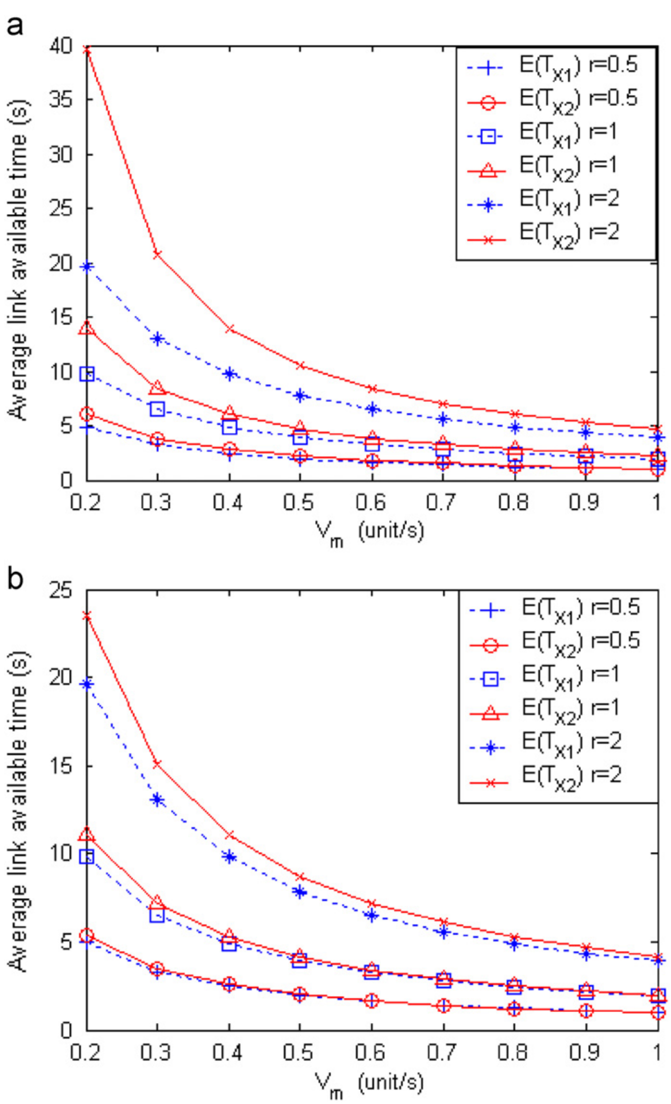

Fig. 3. Numerical results of average link available time. (a) Average RE of 0.2 s and (b) average RE of 1 s.

In practice, the vehicle density and vehicle mobility do not remain the same throughout the day. For example, vehicle density may be much higher during morning and evening rush hours comparing to that during the day time. In this case, the corresponding vehicle mobility may be relatively lower during the rush hours comparing to that during the day time. In order to verify the analytical results as well as to investigate the effects of mobility models presented in this paper under different traffic conditions, a discrete-event simulator is developed using the C++ language. The mobility model used in the simulations is described as follows:

(1) Mobile vehicles with the same transmission range $r=1$ unit are uniformly located in a square area with $S=20\times 20$ square units. (2) The number of mobile vehicles in the network is set to be $N=800$ and $N=200$, which are used to simulate the conditions of a high vehicle density network (degree[1] $d=6.28$) and a low vehicle density network (degree $d=1.57$), respectively. (3) The maximal moving rate V_m of mobile vehicle is ranging from 0.2 to 1 unit/s, and the moving direction is uniformly distributed in the range of $(0,2\pi)$. (4) The velocity only changes at the beginning of REs; the duration of RE is uniform distribution with a mean value ranging from 0.1 s to 1 s. (5) The boundless simulation area concept (Camp et al., 2002) is applied to the simulations to avoid the border effect (Bettstetter, 2001). When vehicle reaches the network boundary, it continues to travel and reappears on the opposite side of the network boundary. Therefore, the mobile vehicles are able to travel unobstructed across the network.

Fig. 4 illustrates the numerical results of average inter-vehicle link-available time obtained from both analytical models and simulations with different relative velocities. From Fig. 4(a), it can be seen that when the average RE interval is 1 second which corresponds to relatively low vehicle velocity, both $E(T_{X1})$ and $E(T_{X2})$ obtained from analysis match the simulation results well. In contrast, as in Fig. 4(b), when average RE interval is 0.1 s which corresponds to relatively high vehicle velocity, $E(T_{X2})$ obtained from the random moving model is able to always match the simulation results well, however, $E(T_{X1})$ obtained from the mobile handover model only approximately matches the simulation results when $V_m \geq 0.8$ unit/s. This indicates that the random moving model is able to describe the vehicle mobility behavior for both high and low velocities. Furthermore, Fig. 4 illustrates that $E(T_{X2})$ obtained from analytical random moving model is able to match the results obtained from the simulations very well for vehicle density of $N=800$ and $N=200$, respectively. Therefore, the random moving model is also able to formulate the average inter-vehicle link available time for both high and low vehicle density conditions.

The average number of link changes to maintain a connection in VANET is evaluated using an exponentially distributed call holding time with an average of 60 s. Fig. 5 shows the numerical results of $E(N_{hc1})$ and $E(N_{hc2})$ obtained from the analytical mobile handover model and the analytical random moving model, respectively. It can be seen that either vehicle velocity V_m increases or the radio transmission range r decreases have significant effects on the increase of the number of inter-vehicle link changes. Furthermore, a comparison of $E(N_{hc1})$ and $E(N_{hc2})$ for different RE interval of 1 second and 0.2 s, respectively is shown in Fig. 5. It can be seen that for a given value of V_m, $E(N_{hc2})$ is always smaller than $E(N_{hc1})$. However, the difference between $E(N_{hc1})$ and $E(N_{hc2})$ decreases when RE interval increases. This fact indicates that the random moving model is able to present the vehicle mobility behavior better than that the handover mobility model does when RE interval is small enough. Fig. 6 shows $E(N_{hc1})$

[1] The average vehicle degree can be approximated as $d \approx N\pi r^2/S$.

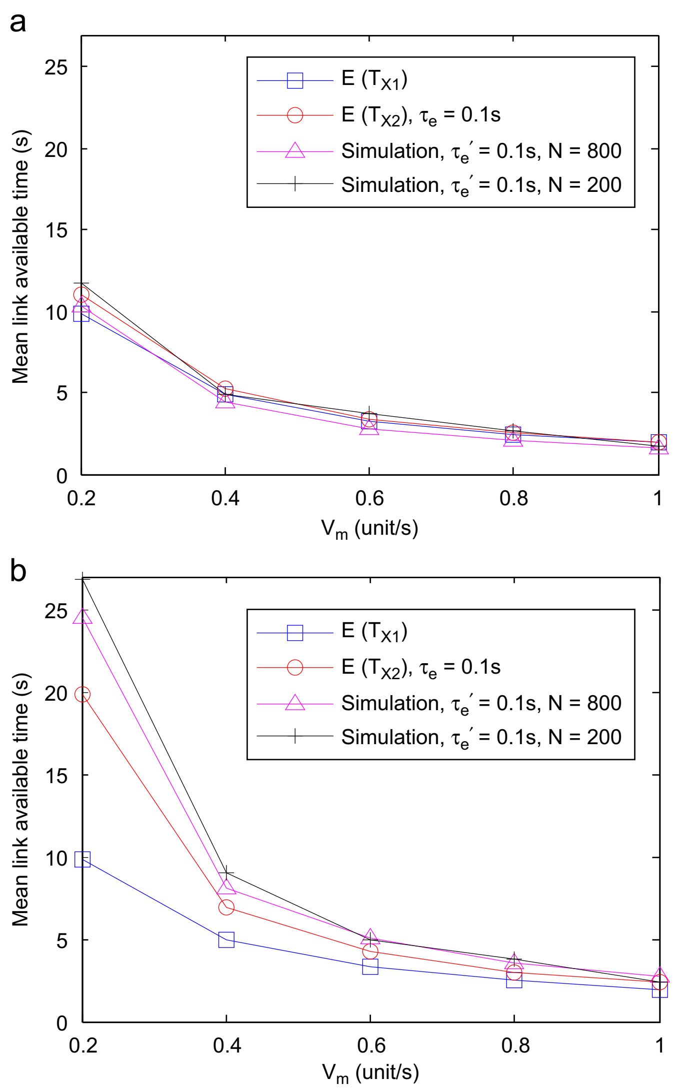

Fig. 4. Average link available time. (a) Average RE of 1 s and (b) average RE of 0.1 s.

and $E(N_{hc2})$ obtained from both analytical models and simulations under high vehicle density condition of $N=800$. It can be found that the number of inter-vehicle link changes increases with an approximately linear slope when V_m increases. However, $E(N_{hc2})$matches the results obtained from the simulations much better than $E(N_{hc1})$ does, especially when RE interval decreases. Note that, in Fig. 6, the simulation results are always lower than the corresponding values of $E(N_{hc2})$ obtained from analytical random moving model. This is because that the simulations take account of inter-vehicles link changes due to non-temporary availability of the neighboring vehicles for handover as shown in Fig. 2. Correspondingly, the analysis of random moving model is done under an assumption that the neighboring vehicles are always available for handover as shown in Fig. 1.

In summary, both vehicle density and vehicle velocity have significant impact on the vehicle mobility as well as the stability in terms of the inter-vehicle link available time and the number of inter-vehicle link changes. However, the numerical results demonstrate that the random moving model is able to present the vehicle mobility behavior well for various types of traffic conditions. Therefore, the analytical random moving model is an important tool in analyzing the effects of mobility on the performance of VANET under different traffic conditions.

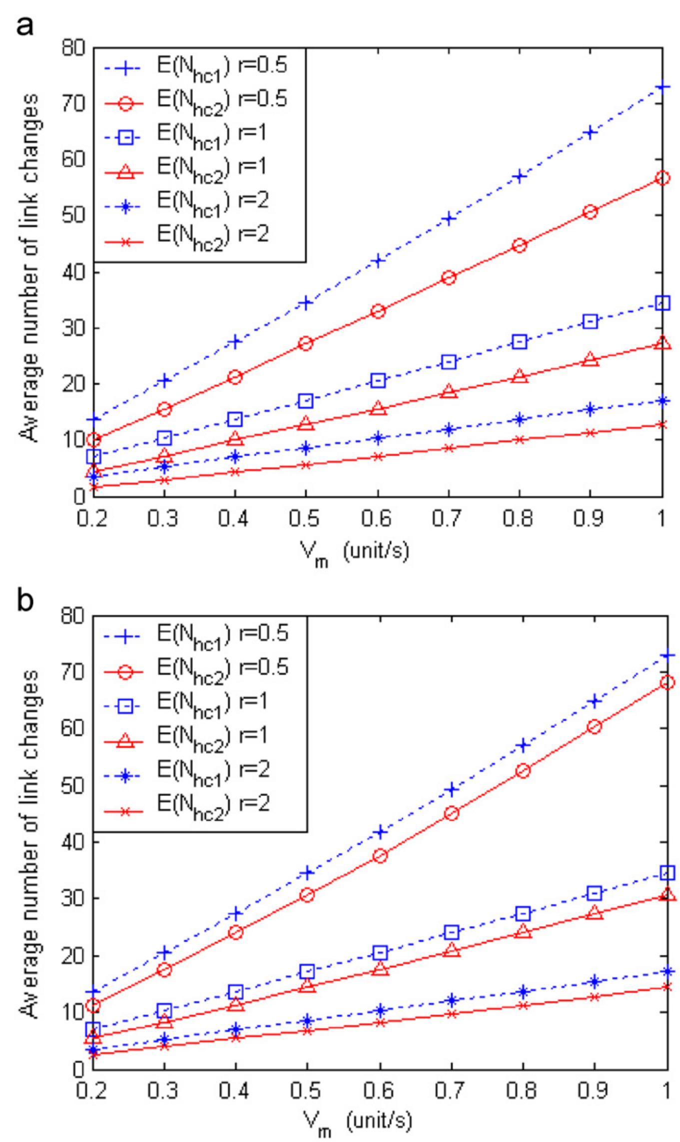

Fig. 5. Numerical results of $E(N_{hc1})$ and $E(N_{hc2})$. (a) Average RE of 0.2 s and (b) average RE of 1 s.

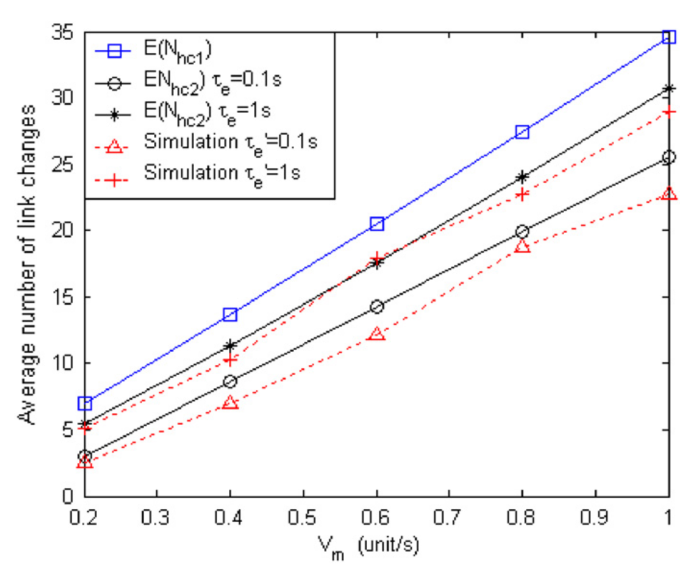

Fig. 6. The average number of link changes, analysis and simulation ($N=800$).

4. Conclusion

This paper presents a methodology for analyzing effects of vehicle mobility in terms of inter-vehicle link available time and the average number of inter-vehicle link changes to maintain an active connectivity in VANET. The relative velocity between two adjacent vehicles is considered in the analysis.

Although the analytical procedures are more complicated, especially for random moving model, but they are able to effectively describe the vehicle mobility behavior. The analytical methodology presented in paper is able to provide useful performance statistics for network designers to be used in wireless channel assigning, threshold selecting for routing exchange and vehicle location updating. For example, inter-vehicle link available time is an important metric for adjusting radio transmission power adaptively, so that the system is able to balance the tradeoff between power consumption and wireless link stability. Moreover, the analytical methodology can be used to validate the simulation scenarios and to calculate confidence intervals of simulations.

References

Ahmed S, Karmakar GC, Kamruzzaman J. An environment-aware mobility model for wireless ad hoc network. Journal of Computer Networks 2010;54(9):1470–89.

Aschenbrucka N, Munjalb A, Campb T. Trace-based mobility modeling for multi-hop wireless networks. Journal of Computer Communications 2011;34(6):704–14.

Bettstetter C. Mobility modeling in wireless networks: categorization, smooth movement and border effects. ACM Mobile Computing and Communication Review 2001;5(3):55–67.

Bettstetter C, Resta G, Santi P. The node distribution of the random waypoint mobility model for wireless ad hoc networks. IEEE Transactions on Mobile Computing 2003;2(3):257–69.

Camp T, Boleng J, Davies V. A survey of mobility models for ad hoc network research. Wireless Communication & Mobile Computing 2002;2(5):483–502.

Chiang, C. Wireless networks multicasting. PhD thesis. Department of Computer Science, Los Angeles, USA: University of California; 1998.

Das SR, Perkins CE, Royer EM. Performance comparison of two on-demand routing protocols for ad hoc networks. IEEE Personal Communications 2001;8(1):16–28.

Fan Li, Wang Yu. Routing in vehicular ad hoc networks: a survey. IEEE Vehicular Technology Magazine 2007:12–22.

Füßler H, Torrent-Moreno M, Transier M, Krüger R, Hartenstein H, Effelsberg W. Studying vehicle movements on highways and their impact on ad hoc connectivity. In: ACM Mobicom 2005; August 2005.

Garcia JJ, Madrga EL. A multicast routing protocol for ad-hoc networks. IEEE INFOCOM 1999:784–92.

Haas ZJ. A new routing protocol for the reconfigurable wireless networks. In: Proceedings of the IEEE 6th international conference on universal personal communications ICUPC97. p. 562–6;1997.

Hong D, Rappaport SS. Traffic model and performance analysis for cellular mobile radio telephone systems with prioritized and nonprioritized handover procedures. IEEE Transactions on Vehicular Technology 1986;35(3):77–92.

Hong GPX, Gerla M, Chiang C. A group mobility model for ad hoc wireless networks. In: Proceedings of the ACM international workshop on modeling and simulation of wireless and mobile systems (MSWiM); 1999.

Jetcheva J, Hu Y, PalChaudhuri S, Saha A, Johnson D. Design and evaluation of a metropolitan area multitier wireless ad hoc network architecture. In: Proceedings of 5th IEEE workshop on mobile computing systems and application (WMCSA 03); 2003.

Johansson P, et al. Routing protocols for mobile ad-hoc networks—a comparative performance analysis. In: Proceedings of the MOBICOM; 1999. p. 195–206.

Kim J, Sridhara V, Bohacek S. Realistic mobility simulation of urban mesh networks. Elsevier Journal of Ad Hoc Networks 2009;7(2):411–30.

McDonald AB, Znati T. A mobility based framework for adaptive clustering in wireless ad hoc networks. IEEE JSAC 1999;17(8):1466–87.

Nadeem T, Dashtinezhad S, Liao C, Iftode L. Trafficview: traffic data dissemination using car-to-car communication. Mobile Computing and Communications Review 2004;8(3):6–19.

Nanda S. Teletraffic models for urban and suburban microcells: cell sizes and handover rates. IEEE Transactions on Vehicular Technology 1993;42:673–82.

Naumov V, Baumann R, Gross T. An evaluation of inter-vehicle ad hoc networks based on realistic vehicular traces. In: MobiHoc '06: Proceedings of the 7th ACM international symposium on mobile ad hoc networking and computing; 2006. p. 108–19.

Navidi W, Camp T. Stationary distributions for the random waypoint mobility model. IEEE Transactions on Mobile Computing 2004;3(1):99–108.

Saha AK, Johnson DB. Modeling mobility for vehicular ad-hoc networks. ACM International Workshop on Vehicular Ad Hoc Networks 2004 p. 91–2.

Santi P, Blough DM. The critical transmitting range for connectivity in sparse wireless ad hoc networks. IEEE Trans. Mobile Computing 2003;2(1):25–39.

Shen C, Du W. Mobility modelling for vehicular communication data dissemination. Computer and information science, studies in computational intelligence, vol. 317. Springer-Verlag; 2010 p. 35–45.

Stojmenovic I. Location updates for efficient routing in ad hoc networks, Handbook of wireless networks and mobile computing. John Wiley & Sons; 2002 pp.451–71.

US Census Bureau TIGER, TIGER/Line and TIGER-Related Products. 〈http://www.census.gov/geo/www/tiger/〉.

Wang KH, Baochun L. Group mobility and partition prediction in wireless ad-hoc networks. Proceedings of IEEE ICC 2002 2002;vol. 2 p. 1017–21.

Zaidi ZR, Mark BL. Mobility Tracking Based on Autoregressive Models. IEEE Transactions on Mobile Computing 2011;10(1).