Connectivity in vehicular ad hoc networks in presence of wireless mobile base-stations

Saleh Yousefi*‡, Eitan Altman†, Rachid El-Azouzi‡, Mahmood Fathy*

* Computer Engineering Faculty, Iran University of Science and Technology, Narmak, Tehran 16846-13114, Iran.
E-mail: {syousefi,mahfathy}@iust.ac.ir
†INRIA, 2004 Route des Lucioles, 06902 Sophia Antipolis, France. E-mail: eitan.altman@sophia.inria.fr
‡ LIA, Université d'Avignon 339, chemin des Meinajaries, Agroparc BP 1228, 84911 Avignon Cedex 9, France.
E-mail: rachid.elazouzi@univ-avignon.fr

***Abstract*—Connectivity in vehicular ad hoc networks tends to be vulnerable. This is mostly because of the influence of road's traffic parameters like traffic flow and vehicle's speed. One possible way to improve the connectivity is to add some nodes with higher transmission range. These nodes also could give some commercial services to the vehicles on roads (i.e. audio/video service, traffic information, etc.). In this paper we study the connectivity in presence of these nodes which we call mobile base-stations. Our approach is based on the work of Miorandi and Altman [11] that transformed the problem of connectivity distance distribution into that of the distribution of the busy period of an equivalent infinite server queue. We study the effects of mobile base-stations on the connectivity distance and number of nodes in a spatial cluster (platoon). In our investigation we use some publicly available statistical data and realistic traffic patterns. Our model can be used to obtain optimum values for number of base-stations and their transmission range in order to achieve intended degree of connectivity.**

Keywords: VANETs, Connectivity, Base-stations, Infinite Server Queuing System.

I. INTRODUCTION

Vehicular Ad-Hoc Networks (VANETs) are special type of Mobile ad Hoc Networks (MANETs), where wireless-equipped vehicles form a network spontaneously while traveling along the road. Direct wireless transmission from vehicle to vehicle make it possible to communicate even where there is no telecommunication infrastructure such as the base stations of cellular phone systems or the access points of wireless dedicated access networks.

This new way of communication has been attracting lots of interest in the recent years in academic and industry community. The US FCC has allocated seven 10 MHZ channels in the 5.9 GHz band for Dedicated Short Range Communication (DSRC) to enhance the safety and productivity of the nation's transportation system [1]. The FCC's DSRC ruling has permitted both safety and non-safety (commercial) applications, provided that safety is assigned priority. IEEE has taken up working on a new standard for VANETs which is called IEEE 802.11p [2]. In addition some other projects outside the US like: PReVENT project [3] in Europe, InternetITS [4] in Japan or Network on Wheels [5] in Germany are aimed to solve challenges. So in a near future, vehicles may benefit from spontaneous wireless communications.

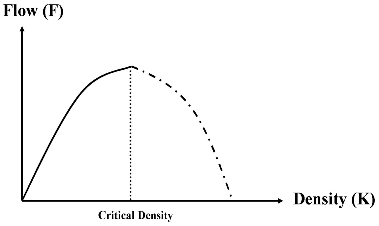


Fig. 1. The relationship between basic parameters in traffic theory

VANETs have many distinctive characteristics and communication challenges as described in [6]. According to FCC frequency allocation one can categorize two main classes of applications for vehicular ad hoc networks. The first category is aimed to improve the safety level in roads. In this case, VANET can be as a complementary for legacy Intelligent Transportation Systems (ITS)[7], [8], in order to enhance the coverage and performance. The second class of applications which is predicted to grow very fast in the near future, is commercial services i.e., comfort applications. Applications is this class offer commercial services like internet access on roads, music download, etc. to passengers. In both beforehand mentioned categories of application, related (i.e. safety or comfort) messages should be exchanged between vehicles.

In order to clarify the challenge which we address in this paper we invoke some basics from traffic theory. From the theory of traffic [9] we know there are three macroscopic parameters including speed (km/h), density (veh/km/lane) and flow (veh/h/lane) which describe the traffic state on a typical road. The values of these parameters are related as so-called fundamental traffic theory equation as follows:

$$F = S \times K \tag{1}$$

where F, S and K are traffic flow, average speed and traffic density, respectively.

Road's traffic can be observed in two different phases as shown in Fig. 1. First when the density is low, drivers can choose their own speed and move as fast as they can or wish.

This state holds until the density reaches a threshold called critical value. This phase is called free-flow traffic flow and is shown by solid lines in the figure. Beyond this density, some vehicles have to control their speed in order to keep safe distance from others. This phase is called forced-flow and is shown with dashed line. If the density increases more, the traffic reaches a jam state where vehicles have to completely stop. Each phase is studied differently in traffic theory's point of view.

Form the communication point of view which we peruse in VANETs, different challenges should be addressed in each traffic state. Obviously, connectivity is the best in the jam state, and is worse at light load corresponding to the free-flow phase in which it might not be possible to transfer messages to other vehicles because of disconnections. However, collision avoidance and shared medium management techniques are trivial in free-flow phase while they are main communication issue which should be addressed in forced-flow traffic state.

Connectivity in VANETs may become poor in some roads, dependent on the traffic flow and vehicls' speed distribution [10]. Since traffic state and speed are not under control of the network and application designer, one possible way to improve the connectivity in this kind of networks is to add some nodes with higher transmission range, named mobile base-stations. They can also offer other services (e.g. internet, video, audio) to vehicles on roads. In this paper we study the connectivity in presence of these nodes. Our approach is based on the work of Miorandi and Altman [11] that transformed the problem of connectivity distance distribution into that of the distribution of the busy period of an equivalent infinite server queue. We study the effects of mobile base stations on the connectivity distance and average number of nodes in a platoon. In our investigation we use publicly available statistical data and realistic traffic patterns. Our model can be used to obtain optimum values for number of base stations and their transmission range in order to achieve intended degree of connectivity.

II. RELATED WORKS

Connectivity in mobile ad hoc networks has a mature body of research and many works discussed it through simulation and/or analytical evaluation [11], [12], [13]. The great body of these works studies the problem in static networks and is more suitable for sensor networks. However, some of them also tried to tackle the problem of connectivity in presence of mobility but their attempts are limited to low-mobility networks and/or usually well-known mobility models. Our work is different from above works in that we consider vehicular mobility which is different from random and/or popular mobility models.

Recently some authors studied the connectivity in vehicular networks specifically. Since due to high relative speed between cars, network's topology changes very fast, some works studied approximations of link life time. In [14] the authors approximate link's lifetime through simulating different scenarios. The authors of [15] used analytical and simulation studies for finding the link's life time. Another category of related research studies the minimum transmission range (MTR) providing connectivity for different type of scenarios and freeways[16]. Very recently in [10] an analytical model is proposed for studying connectivity in VANETs. The proposed model is able to investigates the effect of road traffic parameters and vehicles' transmission range on the connectivity. All these works assume the same transmission range for all vehicles. The obtained results show that for some traffic situation and high speed highways, the connectivity may become very poor.

Since, traffic state and speed are not under control of the network and application designer, one possible way to improve the connectivity in this kind of networks is to add some nodes with higher transmission range (named base-stations in this paper) to the network. A similar idea has been investigated in [12] for general mobile ad hoc networks (MANETs). They tired to improve the connectivity by inserting fixed and wired base stations. Moreover, they assume the transmission range of the base-stations is as large as the transmission range of ordinary nodes. These assumptions make their analysis inapplicable in VANETs. Our work in this paper deals the case when base-station vehicles travel along the road like ordinary vehicles, hence they are mobile and wireless. Furthermore, we assume more realistic assumption in which the transmission range of base-stations is larger than ordinary vehicles.

The rest of this paper is organized as follows: in section III we first define the problem and bring our assumptions. In section IV we propose our analytical model and investigate the connectivity based on an equivalent infinite server queuing model. In section V we numerically evaluate effects of base-stations on the connectivity by using some statistical data from traffic theory and realistic data patterns. Finally the paper will be concluded in section VI.

III. PROBLEM DEFINITION

Assume in a typical uninterrupted highway wireless-equipped vehicles with transmission range $R1$ are moving. In order to improve the connectivity between vehicles, we add a limited number of nodes (mobile vehicles). These nodes have higher transmission range and may offer some commercial services (e.g., internet, video, audio). We denote their transmission range by $R2$. These nodes are not wired to each other and travel along the road the same as ordinary vehicles. In this work we assume the receiver range of base stations and ordinary vehicles are the same, while the transmission range of base stations is larger. We investigate effects of these base stations on the connectivity of the network. Let q be the probability of a node to be base-station and so $p = 1-q$ is the probability that an arbitrary node is ordinary vehicle. Since, base stations are supposed to have higher transmission range (due to special antennas, etc.), they might be expensive and their number and position and also their transmission range should be determined more intelligently. In the following we peruse an analytical model which gives us more facilities to design such a system with optimum settings (i.e. number of nodes and their transmission range).

IV. THE ANALYTICAL MODEL

Assume an observer stands at an arbitrary point of an uninterrupted highway (i.e., without traffic lights, etc.). Vehicles pass the observer with $i.i.d.$ exponentially distributed inter-arrival times with mean $1/\lambda$. It means traffic flow is λ $[veh/h]$. Also assume there are N discrete levels of constant speed $v_i,\ i = 1, \ldots, N$ in the highway where the speeds are $i.i.d.$, and independent of the inter-arrival times. Denote the rate of arrivals of cars at each level of speed by $\lambda_i,\ i = 1, \ldots, N$, thus $\sum_{i=0}^{N} \lambda_i = \lambda$. The arrival process of cars with speed v_i is a Poisson process with parameter $\lambda_i,\ i = 1, \ldots, N$ and these N processes are independent. Moreover the probability of each speed level is $P_i = \lambda_i/\lambda$. Given these assumptions, the inter-arrival time distribution of vehicles with speed v_i is

$$P(T_i > \tau) = 1 - F_{T_i}(\tau) = e^{-\lambda_i \tau} \tag{2}$$

and that of the global arrival process is:

$$P(T > \tau) = 1 - F_T(\tau) = e^{-\sum_{i=0}^{N} \lambda_i \tau} = e^{-\lambda \tau} \tag{3}$$

In order to investigate the connectivity, we use [11] that identified the equivalence between (i) the busy period of an infinite server queue and the connectivity distance in an ad hoc network, and (ii) that between the number of customer served during the busy period and the number of mobiles in a connected cluster (platoon) in the ad hoc network. This is obtained when the inter-arrival times in the infinite server queue have the same distribution as the distance between successive cars and when the service times have the same distribution as the transmission range of the mobiles. We thus have to determine the distribution of L, the random variable representing the distance between two consecutive vehicles. Since speeds are independent we can consider the inter-vehicle distance between vehicles with speed v_i as a thinned Poisson process with rate λ_i. Hence given (2) we will have,

$$P(L_i > x) = 1 - F_{L_i}(x) = P(v_i T_i > x) = e^{-\lambda_i x / v_i}. \tag{4}$$

The distribution of L can be described by the minimum between all inter-vehicles distances obtained for different levels of speed (i.e. L_i). In other words: $L = \min_{i=1,\ldots,N}(L_i)$. Hence L is exponentially distributed with parameter

$$\xi = \sum_{i=1}^{N} \frac{\lambda_i}{v_i} = \lambda \sum_{i=1}^{N} \frac{P_i}{v_i}. \tag{5}$$

Therefore, we may obtain the distribution of inter-vehicle distance as follows:

$$P(L > x) = 1 - F_L(x) = e^{-\xi x} = e^{-\sum_{i=1}^{N} \frac{\lambda_i}{v_i} x}. \tag{6}$$

In order to verify (6) we conducted simulation study for a typical uninterrupted highway. In our simulation we consider 1000 vehicles which move in four levels of constant speed: $100, 150, 175$ and 200 km/h with equal probability of occurrence. The traffic flow is 500 veh/h. We run the simulation model 1000 times with different random seeds and in each run we measured the distribution of inter-vehicle distance for 10 km length. Fig.2 shows the empirical inter-vehicle distance which is obviously very close to the exponential one depicted from equation (6).

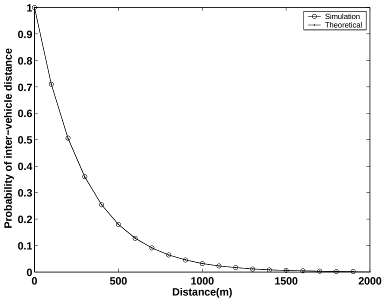


Fig. 2. The theoretical and simulation probability of inter-vehicle distance. The simulation data can be fitted to an exponential distribution with estimated mean 291.90 with 95% confidence interval [289.02, 294.78]. The theoretical mean is 292.17.

Note that if we do not take into account the topology changes due to vehicles' overtaking, we may reach a hyper-exponential distribution for inter-vehicle distance [10]. If there is overtaking then the closest car to point 0 (the observer) at time 0 need not be the first car that will arrive at point 0 after time 0. Thus ignoring this effect of overtaking, as we did in [10], offers an upper bound for inter vehicle distance and thus a lower bound for the connectivity distance (see definition below).

Next, we need to obtain the distribution of R, the random variable representing vehicls' transmission range. Considering our assumptions in previous section, we can describe the distribution function of transmission range as follows:

$$P(R > \alpha) = 1 - H_R(\alpha) = \begin{cases} 1 & \text{if} \quad \alpha < R_1 \\ 1 - p & \text{if} \quad R_1 \leq \alpha < R_2 \\ 0 & \text{if} \quad \alpha \geq R_2 \end{cases} \tag{7}$$

Since inter-vehicle distance is exponentially distributed and the transmission ranges are distributed as in (7), we use equivalent $M/G/\infty$ for investigating the connectivity. From now on, we shall use VANET's terms instead of queuing terms. In the following we study two metrics related to connectivity: 1) the connectivity distance which is defined as the total distance that a packet sent by a given vehicle can reach and 2) the number of vehicles in each spatial cluster (platoon). The former is important because larger connectivity distance leads to larger announcement area for safety applications and better accessibility to roadside equipments (e.g. internet gateway). The latter is important because it shows how many vehicles can hear a vehicle in safety applications and can have data communications in comfort applications.

From [17] we know the Laplace transform of probability density function (p.d.f) of the connectivity distance is defined as:

$$f_d(s) = 1 + \frac{s}{\xi} - \frac{1}{\xi p^*(s)} \tag{8}$$

where $p^*(s)$ is the Laplace transform of $p_0(t)$ defined as below:

$$p_0(t) = e^{-\xi \int_0^t (1-H_R(t))dx} \tag{9}$$

Hence considering (7) after some algebra we may obtain:

$$p^*(s) = \frac{\left(1-e^{-(s+\xi)R_1}\right)}{s+\xi} - \frac{e^{-\xi p R_1}\left(e^{-(s+\xi(1-p))R_2}\right)}{s+\xi(1-p)}$$

$$+\frac{e^{-\xi p R_1}\left(e^{-(s+\xi(1-p))R_1}\right)}{s+\xi(1-p)} + \frac{e^{-sR_2}e^{-\xi((1-p)R_2+pR_1)}}{s} \tag{10}$$

then by substituting (10) in (8) we will reach the p.d.f of connectivity distance. Consequently, the probability of connectivity distance $P_d(\alpha) = P(d > \alpha) = 1 - F_d(\alpha)$ can be found by inverting its complementary cumulative distribution function (c.c.d.f) defined as:

$$P_d^*(s) = \frac{1-f_d(s)}{s} = -\frac{1}{\xi} + \frac{1}{\xi s p^*(s)} \tag{11}$$

where $p^*(s)$ is given in equation (10). Since the resulted expression may not be inverted explicitly, we resort numerical inverting [19] in the following sections.

However, form [18] we find following expression for the average connectivity distance:

$$\mathbb{E}(d) = \frac{1}{\xi P_0} - \frac{1}{\xi} \tag{12}$$

where

$$P_0 = \lim_{t\to\infty} P_0(t) = e^{-\xi((1-p)R_2+pR_1)} \tag{13}$$

As a result the average connectivity distance is obtained as:

$$\mathbb{E}(d) = \frac{1}{\xi}\left(\frac{1}{e^{-\xi\{(1-p)R_2+pR_1\}}} - 1\right) \tag{14}$$

Furthermore, we are able to find the average number of vehicles in a platoon which is given by $\mathbb{E}(N) = \frac{\xi \bar{c}}{v}$ where

$$\bar{c} = \frac{1}{\xi P_0} \tag{15}$$

is the average distance between the beginning of two consecutive platoons [18]. Thus, average platoon size is obtained as below:

$$\mathbb{E}(N) = \frac{1}{P_0} = e^{\xi\{(1-p)R_2+pR_1\}} \tag{16}$$

Discussion. The connectivity analysis performed in this section deals with one-way data transmissions. As is illustrated in Fig.3, when there is a gap in the network, inserting the base-stations (i.e. A) may only help to improve the connectivity for right-to-left data transmissions because A due to higher transmission range can reach B. But still the communication form left-to-right is not possible because B can not reach A. It should be stressed that most of the safety applications just need one-way data transmissions (e.g. when a vehicle announces the approaching vehicles about occurrence an accident).

However, for comfort applications (e.g. internet access on roads) the connectivity should be two-way, because data communication protocols need sending and receiving packets simultaneously. Our model can also cover this case considering following remarks: Let P_{1-way} to be the probability of one-way connectivity (either right-to-left or left-right). Then we denote by $\bar{P}_{1-way} = 1 - P_{1-way}$ the related disconnection probability. Now if P_{2-way} stands for the probability of 2-way connectivity, the following expression always holds:

Fig. 3. One-way and two-way connectivity

$$1 - 2\bar{P}_{1-way} \le P_{2-way} \le P_{1-way} \tag{17}$$

From equation (17) one can find the lower and upper bounds for two-way probability of connectivity. If the probability of one-way connectivity is large enough, then the margins for probability of two-way connectivity will be tight and the results of our model will be more accurate.

V. NUMERICAL STUDY

In order to be able to study the model numerically we should import required model parameters like P_i and v_i appearing in (5) sufficiently. This parameters can be obtained directly based on experimental data. However, in order to have more facilities to investigate the effects of different parameters on the connectivity we present our numerical study based on the following debate. It has been widely accepted in vehicle traffic theory that speeds in the free-flow traffic state are well described by a Normal distribution [9] and some nominal values are provided [15]. Thus speeds are distributed according to the following probability density function:

$$f_V(v) = N(\mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{\frac{-(v-\mu)^2}{2\sigma^2}} \tag{18}$$

where μ stands for average speed and σ is standard deviation of vehicles' speeds. We shall use a truncated version of this distribution to avoid dealing with negative speed or even to avoid getting close to zero speed (the latter would otherwise cause problems in (6) and elsewhere; in fact it can be seen that a speed of zero does not make sense since a car cannot cross the observer if it has speed zero). We thus define two limits for the speed (i.e. v_{min} and v_{max} for minimum and maximum levels of vehicle's speed in a highway, respectively). Hence, by substituting P_i and v_i in (5), we will have:

$$\xi = \lambda \int_{v_{min}}^{v_{max}} \frac{\hat{f}_V(v)}{v} dv \tag{19}$$

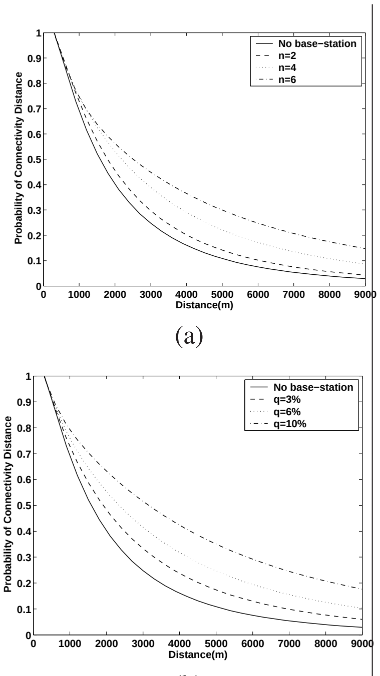
where $v_{min} < v < v_{max}$ and

$$\hat{f}_V(v) = \frac{f_V(v)}{\int_{v_{min}}^{v_{max}} f_V(s)ds} = \frac{2 f_V(v)}{\text{erf}\left(\frac{V_{max}-\mu}{\sigma\sqrt{2}}\right) - \text{erf}\left(\frac{V_{min}-\mu}{\sigma\sqrt{2}}\right)} \tag{20}$$

Here by definition, $\text{erf}(x) = \frac{2}{\sqrt{2\pi}}\int_0^x e^{-t^2}dt$ is the error function. The other important parameters needed to be imported by our model are the maximum and minimum speed of vehicles. Since the area under the normal curve for speeds in $(\mu - 3\sigma, \mu + 3\sigma)$ is about 99.7% of the whole area, in order to take in to account almost all values of speed we take $v_{min} = \mu - 3\sigma$ and $v_{max} = \mu + 3\sigma$. Clearly we do not lose the generality by beforehand mentioned parameter selection and one can import the parameters differently for specific highway based on fully experimental data.

In this paper we focus on effects of parameters related to base-station (i.e. number of base-stations and their transmission range) on the connectivity of resulted hybrid network by using the analytical model presented above. For this purpose we define an integer number n where $R2 = nR1$. This parameter represents the size of the base-station's transmission range in comparison to ordinary vehicles. Furthermore, as mentioned in the previous section, q stands for the fraction of number of base-stations to all vehicles. Recalling the fact that the connectivity is more challenging in sparse traffic state, we should pick up scenarios which fall in free-flow traffic state. In typical free-flow traffic the traffic flow is usually considered below 1000 $[veh/h/lane]$ for freeways and below 500 $[veh/h/lane]$ for other roads [9]. Moreover, the proposed transmission range for DSRC standard is up to 1000 m [1], [2]. In this section we take following nominal values: traffic flow $500[veh/h]$, $R1 = 500$ m and speed in Normally distributed: $N(110, 33)$.

Fig.4 illustrates the improvement of probability of connectivity distance by adding base-stations: (a) when $q = 5\%$ for different base-station's transmission ranges (b) when $n = 4$ for different percentage of base-stations. As one can conclude, the improvement of the probability is noticeable when the number of bas-stations and/or their transmission range is large enough.



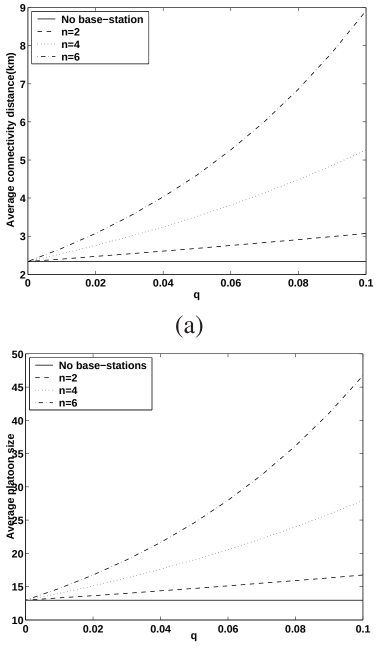
(a)

(b)

Fig. 4. Improvement of connectivity

The Laplace transform of connectivity distance probability is given as equation (11). Although, it may be difficult to find the explicit form for its inversion, we are able to invert it numerically using the Gaver-Stehfest method [19], which permits recovering the probability of connectivity approximately from its Laplace transform sampled at a few points on the positive real axis. Note the probability function is a continuous, non-periodic, function of distance, hence Gaver-Stehfest method is appropriate for our purpose.

The average connectivity distance and average platoon size versus q for different values of n is shown in Fig.5. As one can conclude, unless there is enough base-stations on the road, their transmission range does not have noticeable effect on the studied metrics. For example, when 3% of all vehicles are base-station, even if the transmission range of base-stations is six times larger than the ordinary vehicles, the average connectivity distance is increased just less than 1 kilometer. However, higher number of base-stations show acceptable connectivity distance even with lower transmission range. On the other side, if the transmission range of base-stations is twice the ordinary nodes, even large number of base-stations (e.g. 10%) just improves the connectivity less than 700 meters. It should be stressed that the curves in Fig.5 has been drawn for fixed transmission range and traffic flow.



(a)

(b)

Fig. 5. Effect of transmission range and number of base-stations on (a) average connectivity distance, (b) average platoon size

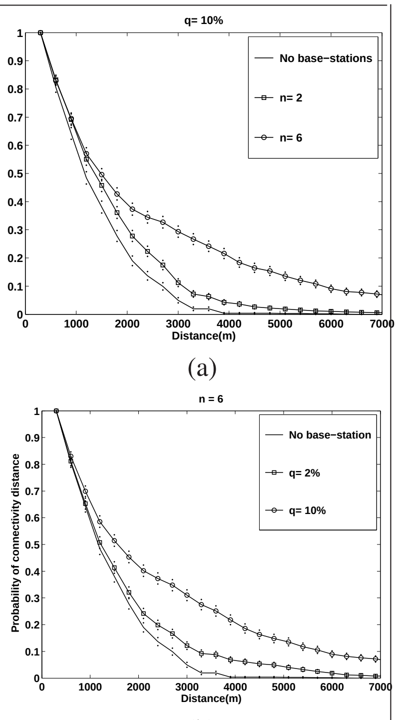
Discussion. Our model presents a tool for setting optimum values for q and n, given some implementation constraints. For example, given desired connectivity requirements (e.g. intended values for average and probability of connectivity distance and/or average platoon size) one can find the minimum number of base stations considering the constraint on their transmission range. This issue has practical importance because a service provider may prefer to use minimum number of base-station on the road.

The issuing policy of base-stations defining the rate of their departure and their speed also can be determined based on the following debate. Let λ_{veh} and λ_{BS} be traffic flow (of ongoing traffic) and departure rate of the base-stations. Since in our model both are assumed to be Poisson process, $\lambda = \lambda_{veh} + \lambda_{BS}$. Thus we can write $q = \frac{\lambda_{BS}}{\lambda_{BS}+\lambda_{veh}}$ and as a result given the traffic flow, the departure rate of base-stations can be determined form the above analytical model. Furthermore the speed of base-stations is also could be chosen the same as speed process of ordinary vehicles. Note the traffic flow and average speed should be imported to our model based on experimental observation of the under-study highway.

A. *Experimental study*

In order to have more insights about the effects of base-stations on the connectivity, we perform some measurement on the data published by FleetNet project [20] which is available on the Web [1]. This data was originally generated by DaimlerChrysler's internal macroscopic simulator called FARSI. This simulator uses realistic speeds, distances, and macroscopic properties like traffic flow and lane usage for German autobahns. The published data is representing about 12.5 km of multi-lane highways for one minute duration including 120 time slots. Although the data is limited in both length and duration, it is well-known realistic data. Here we perform measurements on some part of this data which is in agreement with our model assumptions (i.e. free-flow traffic state). Fig.6 shows Some initial results.

In the scenario illustrated in Fig.6, we picked up 2-lane highway with $2[veh/km/lane]$ density from the available FleetNet patterns. Furthermore the transmission range of vehicles is set to 500 m. As is illustrated in the figure, the behavior of the connectivity in presence of the base-stations, predicted by our model is confirmed by the observation. In this figure, the measurements are plotted together with dots delimiting the 95% confidence interval.



(a)

(b)

Fig. 6. Effect of (a) transmission range and (b) number of base-stations on the probability of connectivity distance measured from a scenario in FleetNet traffic patterns

VI. CONCLUSION

We study the improvement of connectivity in VANETs through adding some extra nodes. These nodes (named wireless mobile base-stations) is supposed to have higher transmission range and may offer some commercial services while traveling along the road. In order to investigate the connectivity, we invoke an equivalent infinite server queueing model. We obtain the Laplace transform of probability of connectivity distance and explicit forms for average connectivity distance as well as the average number of vehicles in a platoon. Then we perform numerical study for investigating effects of these base-stations on the connectivity of resulted hybrid network. In our investigation, some publicly available statistical and realistic traffic patterns are used. Our proposed analytical model can be used to find the optimum values for number of base-stations and their transmission range in order to achieve desired degree of connectivity.

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