Quantitative Analysis of the VANET Connectivity: Theory and Application

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***Abstract*—Nowadays, Vehicular Ad hoc NETworks (VANETs) attract more and more attentions both from academia and industry. Although it has achieved much success in the research field, large-scale deployments of VANETs are still lacking. One important reason is that both governments and companies are doubtful about the performance of VANETs in large-scale deployment in real world. There are many protocols competing with each other and we don't know which one will become the standard. So it is difficult for us to estimate the network performance when we even do not know which protocol to use. However, we can circumvent the problem by analyzing the network connectivity, which is closely related to the network performance. We give a thorough theoretical analysis of the VANET connectivity using bond percolation model and Bollobás model in different scenarios. We discover the quantitative relationship among network connectivity, vehicle density and transmission range. Given the vehicle density, we can calculate the minimum transmission range to achieve good network connectivity. Simulations conducted in a large scenario validate our analysis. Our results not only give us insights about the properties of the network topology, but also have great meanings in real world, which can guide the deployment of VANETs.**

I. INTRODUCTION

Vehicular Ad hoc NETworks (VANETs) are a special type of Mobile Ad hoc NETworks (MANETs), which are built up from vehicles. Vehicles can communicate with each other using wireless links. Sometimes, VANETs also contain Road Side Units (RSUs) in order to improve the network performance. It is a promising technology, which has a wide application area from safety to entertainment and attracts attentions both from academia and industry. Regardless of its progress in the research field, large-scale deployments of VANETs are still missing. One barrier facing us is that the technology is still not mature for commercial use and current commodities in the market are too expensive for large deployment. Another barrier which is more important is that both governments and companies are doubtful about the performance of VANETs in large-scale deployment in real world. Because deploying such huge facility as VANETs costs large amounts of resources, it is crucial that governments and companies make a thorough estimation and comparison of the benefits and the costs of VANETs.

Nowadays, there are still many protocols competing with each other and we do not know which one will defeat others and finally become the standard to real deployment. Such situation stresses the difficulty for us to estimate the performance of VANETs. *How can we calculate the loss rate and throughput, which are often used to measure the performance of a network, when we even do not know which network protocol to use?* However, we can circumvent this problem by analyzing the connectivity of VANETs. No matter which network protocol is used in VANETs, the performance of the protocol is closely related to the connectivity of the network. So if we can have a good understanding of the connectivity of VANETs, we can have a good estimation of the performance of VANETs.

In MANETs, analysis of the network connectivity is once a hot topic. Researchers use both theoretical analysis and simulations to study the problem [1][2][3]. Simulation results show the relationship between network connectivity and the factors influencing it, and theoretical analysis gives people a better understanding of the reasons behind the simulation results. In recently hot research in VANETs, there are also some studies trying to analyze the connectivity of VANETs. However, VANET has its own characteristics which make it different from MANET. One important characteristic is that the scenario of VANETs is in a city where the movement of vehicles is bounded by streets. But in most scenarios of MANETs, mobile nodes can move freely. This difference raises significant difficulty on theoretical analysis of the connectivity of VANETs. There are few previous studies that have given a thorough theoretical analysis on the connectivity of VANETs. Works such as [4] use some results of MANETs [1] to study the problem in VANETs. Other works mainly rely on simulations to analyze the connectivity of VANETs [5][6][7][8][9]. Theoretical analysis is still lacking.

In this work, we give a theoretical analysis of the connectivity of VANETs. For different transmission range, we use different models. When the transmission range is no longer than several hundred meters, we use bond percolation theory to analyze the problem; when it is several thousand meters, which is much longer than the distance between two intersections, we employ Bollobás model. Our main contributions are:

- We give a theoretical analysis of the connectivity of VANETs and discover quantitative relationship among network connectivity, vehicle density λ and transmission range r. Based on bond percolation model and Bollobás model, we get two indicators, namely p and Bollobás number, for the network connectivity, which can be calculated from λ and r. For each indicator, there is a threshold value. Below the threshold value, the network connectivity is bad; above the threshold value, it is good.

Our analysis gives us some insights about the properties of the network topology of VANETs.
- We conduct simulations in a large scenario. Simulations in some previous studies are conducted in relatively small scenarios and have problems when applied to large scenarios. But our simulations do not have such problem. The simulation results are consistent with our analysis and give us a better understanding of the network connectivity in a large scenario.
- We discuss the application of our results in deployment of VANETs in real world. A large transmission range can have good network connectivity, but it can also cause serious collisions in wireless links. So it is a tradeoff for governments and companies to choose a proper transmission range in deployment. Given vehicle density, our results can calculate the minimum transmission range to achieve good network connectivity. Below the minimum transmission range, although collisions might be few, the overall performance of VANETs can be disappointing due to the bad network connectivity. So our analysis can help us do the tradeoff.

The rest of the paper is organized as follows. Section II introduces some related work. In section III, we give a theoretical analysis of the connectivity of VANETs using percolation theory. In section IV, we conduct simulations to validate our analysis. Section V gives a discussion of our results in application. Finally the conclusions are drawn in section VI.

II. RELATED WORK

Some works have been done to analyze the connectivity of VANETs. Most of them use simulations to analyze the problem. Ho et al. [10] analyze the connectivity of a special vehicular ad hoc network, which is built upon buses. Through simulations, they discuss the impacts of various transport elements on network connectivity, including topology, vehicle traffic and traffic signals. Artimy et al. [5][6] also use simulations to study the relationship between network connectivity and transmission range. Their results show that when there are traffic jams at intersections, the minimum transmission range is not largely influenced by the vehicle density. In [7], Fiore et al. give an analysis of network connectivity using different mobility models. They conduct a number of simulations to study the network topology and explain the physical reasons behind the special connectivity dynamics. Marfia et al. [8] use both realistic traces and simulation traces to study the benefit of RSUs on VANETs. They propose that using RSUs vehicle-to-vehicle communication can avoid long wireless multi-hop paths and the whole performance of the networks can be improved. While these works get interesting and meaningful results from simulations, theoretical analysis is still needed to improve our understanding of the properties of VANETs.

Different from these works, Michel et al. [11] use a novel approach, namely stereoscopic aerial photography, to study the relationship between vehicular mobility and the connectivity of VANETs. Based on photography technology, they get a series of snapshots of the city of Porto. Then they get the locations of thousands of vehicles from the snapshots. They argue that their data are more realistic than results got from simulations. Furthermore, they state that their data cover the vehicles in the city of Porto, whose scenario is much larger than those in the small-scale simulations or testbeds in other works. However, the duration of their analysis is too short compared to the connectivity duration. They only analyze static network characteristics from their data and do not give a theoretical explanation to their results.

Theoretical analysis of the network connectivity is once popular in MANETs [1][2][3]. The results of previous works explain the influence of various factors on the network connectivity, which give us a good understanding of the network topology in MANETs. In VANETs, such studies are still lacking. In [4], Kafsi et al. attempt to analyze the VANET connectivity both through theoretical study and simulation results. In their theoretical analysis, they use percolation theory to analyze the network connectivity. However, when transmission range is very large, Bollobás model is more suitable than percolation model.

III. THEORETICAL ANALYSIS

In this section, we use percolation theory to construct the relationship among network connectivity, vehicle density λ and transmission range r. Firstly, we give some assumptions before we begin our analysis.

- For each road, the incoming rate of vehicles follows Poisson distribution with parameter λ. Actually, it's not a strong assumption, as it is widely accepted in transportation engineering [12][13]. Then we can use the parameter λ to denote the vehicle density.
- Every vehicle is equipped with electronic devices so that they can communicate with each other through wireless links. The transmission range is r, which means if the distance between two vehicles is no more than r, they are connected by a wireless link.
- The network should be large. As VANET is usually aiming at providing service to a whole city, the network will be large enough for us to conduct our analysis using bond percolation model and Bollobás model.

Our analysis can be divided into two parts. When the transmission range is no more than several hundred meters, which is comparable to the length between two intersections, we use bond percolation model to analyze the network connectivity; when the transmission range is very large, we use Bollobás model.

A. Bond Percolation Model

1) Square bond percolation process: Every road segment between two intersections can be regarded as a bond. If the road segment is covered by a sequence of connected vehicles, the *bond*, which denotes the road segment, is *open*; otherwise, the bond is *closed*. When the transmission range is small, we can assume that whether a bond is open or not is independent from other bonds. Then based on this assumption and the three assumptions above, it is safe for us to employ a *square bond* percolation process for the network. We define a probability p as follows.

- p: A road segment between two intersection is covered by a sequence of connected vehicles with probability p. It also means a bond is open with probability p.

Then a bond is closed with probability $1-p$, which means there is at least one vehicle moving on this road segment is not connected to other vehicles on it with probability $1-p$. So we have transformed the connectivity of vehicles on a road segment to the problem that whether the bond is open or closed. Then the connectivity of the whole network can be denoted by the connectivity of open bonds.

From percolation theory, we know that for a *square bond* percolation process, the connectivity of open bonds is closely related to p [14]. If two adjacent bonds are all open, they are regarded as directly connected; if a bond can reach another bond via a path on which the bonds are all open, they are regarded as indirectly connected. A bond cluster consists of open bonds which are directly or indirectly connected. If $p < 0.5$, most of the clusters are of small size; if $p > 0.5$, most of the clusters are of big sizes [14]. The size of clusters grow dramatically when p jumps from below 0.5 to above 0.5 [14]. So we can infer that the connectivity of VANETs will be in a good state if $p > 0.5$ and be in a bad state if $p < 0.5$. There is a jump for the network connectivity when p is 0.5. So our main problem now is to calculate the probability p. If we can use vehicle density λ and transmission range r to calculate p, we can have an good estimation of the network connectivity.

2) The relationship between p, λ and r: Now, we begin to discover the relationship between p, λ and r. First of all, we define a term S as follows.

- S: For a certain vehicle on a road, S is the distance from this vehicle to the furthest vehicle that can be connected to it via one-hop or multi-hop wireless links.

Then using S we define a function $h(x)$ as the probability that S is larger than x. Formally,

$$h(x) = \mathbb{P}(\mathcal{S} > x). \tag{1}$$

In [1], similar definition has been used to analyze the connectivity of MANETs. And it has given the precise expression of $h(x)$:

$$h(x) = \begin{cases} 1, & \text{if } 0 \le x < r; \\ \displaystyle\sum_{i=0}^{\lfloor x/r \rfloor} \frac{(-\lambda e^{-\lambda r(x-ir)})^i}{i!} & \\ \displaystyle - e^{-\lambda r} \sum_{i=0}^{\lfloor x/r \rfloor - 1} \frac{(-\lambda e^{-\lambda r(x-(i+1)r)})^i}{i!}, & \text{if } x \ge r. \end{cases} \tag{2}$$

In[1], it further shows that h satisfies the following integral equation:

$$h(x) = \lambda e^{-\lambda x} \int_{x-r}^{x} h(y) e^{\lambda y} dy. \tag{3}$$

So, if we can find the relationship between $h(x)$ and p, we can use λ and r to calculate p. We guess that $h(x)$ is the same order with p^x when x grows to infinity. More precisely, we expect that there exists two positive numbers c_1, c_2 such that

$$c_1 p^x \le h(x) \le c_2 p^x. \tag{4}$$

In order to prove Inequality (4), we need the following lemma.

Lemma 1. *Given $r, \lambda > 0$, when $r\lambda \neq 1$, the following equation has exactly two roots in the interval $(0, 1)$:*

$$x^r \log x + \lambda e^{-\lambda r} = 0. \tag{5}$$

When $\lambda r = 1$, this equation has exactly one root in $(0, 1)$.

Proof: Denote $f(x)$ by $f(x) = x \log x + \lambda r e^{-\lambda r}$. It is easy to see that x is a root of f if and only if x is a solution of Equation (5). When $x \to 0$ or $x \to 1$, $f \to \lambda r e^{-\lambda r} > 0$. Observe that

$$f''(x) = \frac{1}{x} > 0,$$

which implies that f is strictly convex on $(0, 1)$. Let the derivative of f be zero, then we find f reaches minimum at $x = e^{-1}$:

$$f(e^{-1}) = -e^{-1} + \lambda r e^{-\lambda r} \le 0,$$

which will be strict inequality when $\lambda r \neq 1$. By the continuum and convexity of f we can conclude that f has exactly one root in $(0, e^{-1})$ and another root in $(e^{-1}, 1)$, respectively, whenever given $\lambda r \neq 1$. When $\lambda r = 1$, e^{-1} is the only root of f. ■

Theorem 2. *We denote by p the root of Equation (5) other than $e^{-\lambda}$ when $\lambda r \neq 1$, or just $e^{-\lambda}$ when $\lambda r = 1$. Then there exists two positive constants c_1, c_2 such that for any $x > 0$,*

$$c_1 p^x \le h(x) \le c_2 p^x, \tag{6}$$

Proof: Let $g_c(x) = cp^x$. It is easy to check that g_c satisfies Equation (3). By the linearity we know that $h - g_c$ also satisfies Equation (3).

For the lower bound, since $h(x) \equiv 1$ when $x < r$, we may choose a sufficiently small positive c such that

$$h(x) - g_c(x) = h(x) - cp^x > 0.$$

Now we are going to prove that $h - g_c > 0$ on the whole $(0, +\infty)$. Suppose on the contrary, we can pick $x_0 = \inf_{x \ge 0} h(x) - g_c(x) \le 0$. Apparently $x_0 \ge r$. Therefore, we have

$$h(x_0) = \lambda e^{-\lambda x_0} \int_{x_0 - r}^{x_0} h(y) e^{\lambda y} dy \le 0,$$

which implies there exists $x' \in (x_0 - r, x_0)$ such that $h(x') - g_c(x') \le 0$, contradicting to the definition of x_0.

Using the same argument we can prove the right side of the inequality. ■

Remark 3. *From this theorem we conclude that $\lim_{x \to +\infty} h(x)^{1/x} = p$. And it is easy to calculate p by using Newton-Ralphson method on Equation (5).*

3) Theoretical discussion: From Theorem 2, we conclude that p is a function of r, λ:

$$p = p(r, \lambda). \tag{7}$$

Though this is an implicit function, it is easy to calculate the value of p by many methods, such as Newton-Raphson method. Intuitively, p is an increasing function of both r and λ, which can be proved rigorously. Figure 1 shows all pairs of (λ, r) that satisfies $p = 0.5$. All the theoretical analysis, as well as Figure 1, ensures us for each λ, there exists a minimum transmission range r_0 such that for any $r > r_0$, p will be larger than 0.5, and vice versa. For each r, similar conclusion can be easily obtained.

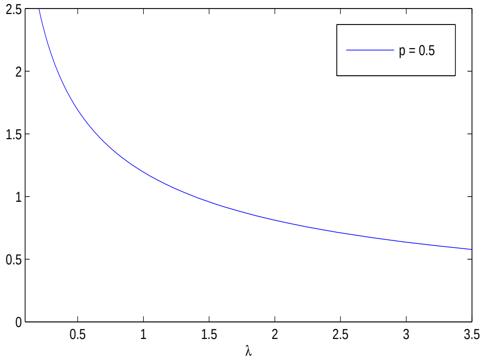


Fig. 1. r vs. λ when $p = 0.5$. r is normalized by the distance between two intersections.

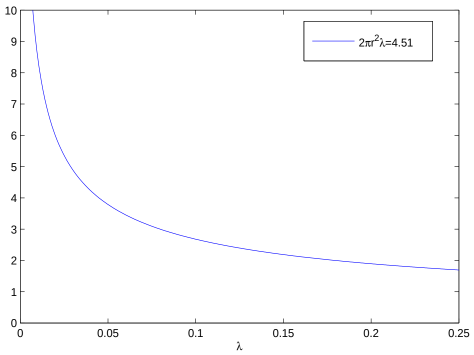


Fig. 2. r vs. λ when $2\pi r^2 \lambda = 4.51$. r is normalized by the distance between two intersections.

B. Bollobás Model

1) Theoretical analysis: When the transmission range is large, it is too rough to assume that whether a bond is open or closed is independent from other bonds. In this case, Bollobás model is more suitable to be used in the analysis. Firstly, we should recall some assumptions of Bollobás model. Bollobás model assumes that there is a Poisson precess $\mathcal{P}$ of intensity one in the plane $\mathbb{R}^2$, and two points of $\mathcal{P}$ are connected if the distance between them is less than r. Denote by G_r the infinite graph. Now we present an important result from [15].

Theorem 4. *There exists a constant, denoted by a_c, such that if $\pi r^2 > a_c$ there will exist an infinite connected cluster in G_r with probability one; if $\pi r^2 < a_c$, all the connected clusters will be finite size with probability one. Furthermore, with confidence 99.99%, a_c lies between 4.508 and 4.515.*

Remark 5. *Actually, when $\pi r^2 > a_c$ most clusters' sizes are much larger than those when $\pi r^2 < a_c$. More exactly, there will be a phase transition when πr^2 jumps from below a_c to above a_c, just the same case as bond percolation model when $p = 0.5$.*

Now we are going to apply Bollobás model in our problem. When $r \gg 1$, all the vehicles can be seen as to uniformly distribute on the plane and follow Poisson distribution. Next, in order to meet the requirements of the theorem, we should make a change according to the scale. Note that the expected number of vehicles in a unity square measure is 2λ. Therefore the modified transmission range should be $r\sqrt{2\lambda}$. Therefore, in order to determine whether it surpasses the threshold we need only to compare $2\pi\lambda r^2$ with $a_c \approx 4.51$.

2) Theoretical discussion: From the analysis above, we know that when r is very large, we can use $2\pi\lambda r^2$ to estimate the network connectivity. We denote $2\pi\lambda r^2$ by Bollobás number.

$$\text{Bollobás number} = 2\pi\lambda r^2.$$

According to our analysis, we can just compare Bollobás number with $a_c \approx 4.51$. When Bollobás number < 4.51, the network connectivity is bad; when Bollobás number > 4.51, the network connectivity is good. It is very similar to p in bond percolation model. We can easily see that Bollobás number is also an increasing function of both r and λ. Figure 2 shows all pairs of (λ, r) when Bollobás number $= 4.51$. Also it is easily to see that for each λ, there exists a minimum transmission range r_0 such that for any $r > r_0$, p will be larger than 0.5, and vice versa. For each r, similar conclusion can be easily obtained.

IV. SIMULATION

In the previous section, we give a theoretical analysis to the connectivity of VANETs. In this section, we conduct simulations to validate our analysis.

A. Simulation Settings and Metrics

We conduct simulations in a large scenario. The area has 50 horizontal roads and 50 vertical roads. The distance between two parallel roads is 250 $meters$. The simulation area is about 150 $square\ kilometers$ large, nearly a small city. Many previous studies conduct simulations in a rather small area [4][7]. As the deployment of VANETs mainly aims at a whole city, it is necessary to conduct simulations in a large scenario.

The mobility model we use is similar to Manhattan Mobility Model [16]. There are also many other mobility models designed for VANET simulations. But because the target of our work is not to compare different mobility models, we do not consider them here. Each vehicle has a max velocity of

30 m/s. For each second, each vehicle chooses a random velocity smaller than its max velocity. Vehicles can choose to turn left, right or go straight at intersections. The choice is probabilistic: the probability of going straight is 0.5 and the probability of turning left and right is both 0.25. The simulation time is 300 $seconds$.

In our simulations, we use N_c to measure network connectivity, which is defined as follows.

- N_c: number of clusters. If two vehicles are within each other's transmission range, they are connected by a single-hop wireless link. A cluster consists of a group of vehicles in which every vehicle is connected to other vehicles by single-hop or multi-hop wireless links. Then N_c is the number of different clusters in the network.

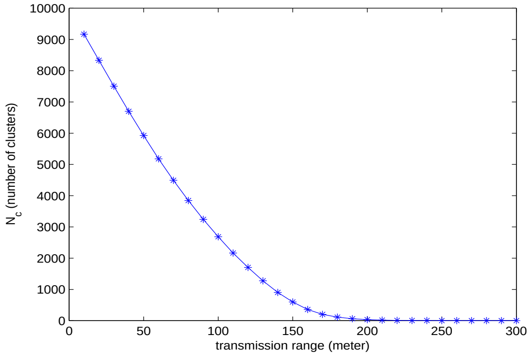
In each simulation, we calculate the number of clusters in every second and use the average of them as N_c for the simulation. Obviously, a small N_c means a good network connectivity. There are also some other metrics that can be used to measure the network connectivity, such as the average size of clusters. Given the network, if the number of clusters is small, the average size of clusters will be big. Due to the limited space, we only consider N_c here. But even using other metrics, our theoretical analysis is still correct.

B. Simulation for Bond Percolation Model

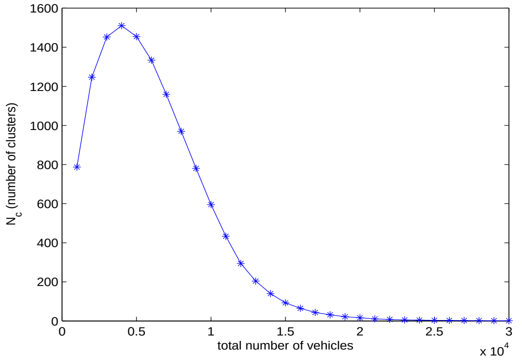
As bond percolation model is applicable to scenarios where transmission range r is not very large, we set r to several hundred meters, which is comparable to the length between two intersections.

1) The impact of transmission range: In the first group of simulations, we fix the vehicle density λ and change the transmission range r. The total number of vehicles in the simulation area is fixed to 10000, which means λ is about 2 $vehicles/lane$. r varies from 10 $meters$ to 300 $meters$. The results are shown in Figure 3(a). We can easily see that when r increases, number of clusters N_c decreases. It means an increase of transmission range can result in better network connectivity. Furthermore, we observe that when r is about 200 $meters$, there is a jump for N_c. From Theorem 2, we can calculate p is about 0.5 when r is 200 $meters$ and λ is 2 $vehicles/lane$. So our simulation result here is consistent with our analysis.

2) The impact of vehicle density: In the second group of simulations, we fix the transmission range r and change the vehicle density λ. r is fixed to 150 $meters$. The total number of vehicles varies from 1000 to 30000, which means λ varies from 0.20 $vehicles/lane$ to 4.08 $vehicles/lane$. The results are shown in Figure 3(b). When the total number of vehicles increases, number of clusters N_c first increases and then decreases. This is because when the vehicles are few, the network connectivity is not so good. More vehicles only result in more isolated clusters. However, when the number of vehicles increases to some degree, the small isolated clusters aggregate to become big clusters. So N_c begins to decrease. Moreover, when the total number of vehicles increases to about 16000, there is a jump for N_c, after which the network connectivity becomes so good. When the total number of vehicles is 16000, the vehicle density is about 3.26 $vehicles/lane$. The probability p is about 0.5 when r is 150 $meters$ and λ is 3.26 $vehicles/lane$ based on Theorem 2. The simulations again accord with our theoretical analysis that when p is 0.5, there will be a jump for the network connectivity.



(a) N_c vs. transmission range r. The total number of vehicles is fixed to 10000.



(b) N_c vs. total number of vehicles. The transmission range r is fixed to 150 m.

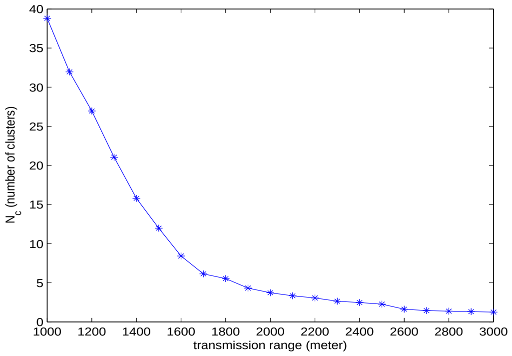
Fig. 3. Simulation for Bond Percolation Model

C. Simulation for Bollobás Model

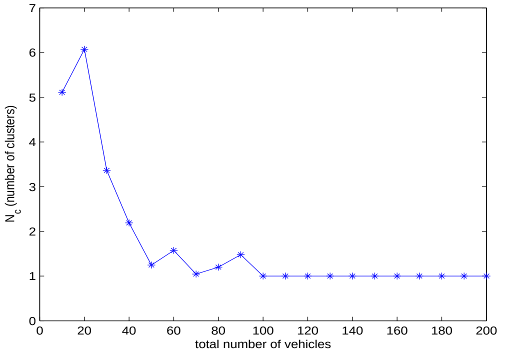
Since Bollobás model is applicable to scenarios where transmission range r is large, we set r to several thousand meters, which is much longer than the length between two intersections.

1) The impact of transmission range: In the first group of simulations, we fix the vehicle density λ and change the transmission range r. The total number of vehicles in the simulation area is fixed to 80, which means λ is about 0.016 $vehicles/lane$. r varies from 1000 $meters$ to 3000 $meters$. The results are shown in Figure 4(a). When r increases, number of clusters N_c decreases, which means the network connectivity becomes better. There is a jump for N_c when r is 1700 $meters$, at which point Bollobás number is about 4.65. From Bollobás model, we know that when Bollobás number is 4.51, there is a jump for the network connectivity. So our simulation result here accord with our theoretical analysis.

2) The impact of vehicle density: In the second group of simulations, we fix the transmission range r and change the vehicle density λ. r is fixed to 2500 $meters$. The total number of vehicles varies from 10 to 200, which means λ varies from 0.002 $vehicles/lane$ to 0.041 $vehicles/lane$. We omit the results when the total number of vehicles is more than 200 here, because the network connectivity becomes so good and N_c does not vary after that in our simulations. The results are shown in Figure 4(b). When the total number of vehicles increases, number of clusters N_c first increases and then decreases, which is similar to the simulations for bond percolation model. The reason is also similar. More vehicles at first only generate more isolated clusters and then aggregate to big clusters. When the total number of vehicles increases to about 40, there is a jump for both for N_c. Again, we can calculate the Bollobás number, which is 5.13 when the total number of vehicles is 40 and 3.84 when the total number of vehicles is 30. So the simulations again accord with our theoretical analysis using Bollobás model.



(a) N_c vs. transmission range r. The total number of vehicles is fixed to 80.



(b) N_c vs. total number of vehicles. The transmission range r is fixed to 2500 m.

Fig. 4. Simulation for Bollobás Model

V. APPLICATION IN REAL WORLD

From our theoretical analysis, we can get some insights about the connectivity of VANETs, which can also guide the deployment of VANETs in real world.

If there are not many vehicles in a city, which means the vehicle density λ is low, the transmission range r should be large in order to get a good network connectivity. So when deploying VANET in the city, government and companies should be aware of such situation and choose electronic devices with large power. As for large transmission range, Bollobás model is more suitable for such scenario. From our analysis, we know that there is a jump for the network connectivity when Bollobás number is about 4.51. So we can use Bollobás model to calculate the exact value for the minimum transmission range to achieve good network connectivity. Below the minimum transmission range, the network connectivity is bad. On the other hand, we know that a large transmission range can cause serious collisions in wireless links, which can reduce the performance of wireless networks. So it's a tradeoff to choose a smaller transmission range with worse network connectivity but fewer collisions and a larger transmission range with better network connectivity but more collisions. At least, our theory tells us that there is a minimum transmission range, below which the overall performance of the network might be disappointing due to the bad network connectivity. Further discussion about the tradeoff will be a part of our future wok.

For cities with large amounts of vehicles, our results state that even a small transmission range is enough to obtain good network connectivity. The exact value of the minimum transmission range can be calculated by Theorem 2 using bond percolation model. So in deployment vehicles should just be equipped with electronic devices with a small transmission range. Such devices need less power and save energy, which also meets the requirement of "GREEN EARTH". However, there is also a pitfall here. Large amounts of vehicles do not mean large amounts of vehicles equipped with these electronic devices. In our analysis, we assume that all vehicles are equipped with the devices and use vehicle density to denote them. But it is natural that for a new technology, there will be a long process until reaching a high market penetration rate. So although a city might have a large quantity of vehicles, the exactly vehicle density equipped with the electronic devices can still be very low. In such situation, a large transmission range is still desirable in order to get good network connectivity.

Another thing we should take into account is that even in the same city, the vehicle density is different at different time. Usually the vehicles running on the roads in the daytime are much more than those at night. So the minimum transmission range varies during the day. If the transmission range is fixed to provide good network connectivity all the day, it will be too large for the daytime, which not only wastes energy but also brings more collisions. In such situation, the software radio technology can be used to adjust the transmission range according to different vehicle density at different time.

VI. CONCLUSION

In this paper, we studied the connectivity of VANETs both using theoretical analysis and simulations. Firstly, we use bond percolation model and Bollobás model to analyze the problem theoretically. We find the quantitative relationship among network connectivity, vehicle density λ and transmission range r. Furthermore, we conduct simulations in a large scale scenario to validate our theoretical analysis. The simulation results accord with our analysis. Our results not only gives us insights about the network connectivity, but also can be applied to estimate the connectivity of VANETs. Given vehicle density, we can calculate the minimum transmission range to achieve good network connectivity, which can guide the deployment of VANETs in real world.

In the future, we will take the impact of RSUs into consideration. Furthermore, we will study the impact of transmission range and vehicle density on collisions in wireless links. Given vehicle density, we want to get a proper choice of transmission range to obtain a good tradeoff between network connectivity and collision, which will greatly help governments and companies in planning and deploying of VANETs.

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