Performance Analysis for Traffic-Aware Utility in Vehicular Ad Hoc Networks

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Abstract. As one of the key research topics in Vehicular Ad Hoc Networks (VANETs), analysis of traffic-aware utility is always difficult to be solved properly. In order to make the utility function be more suitable for the realistic network environment, a performance analysis for the utility function of different traffic is conducted in this paper. We consider two types of traffic, best effort traffic and real time traffic, and develop the form of utility functions for various traffic in VANETs. To model the dynamic features in VANETs more generally, the Poisson process and the traffic flow theory are used to describe the vehicle's mobility. According to the theoretical analysis proposed in this paper, the conditional probability density function (pdf) of utility function for different traffic in VANETs can be deduced, which is much easier to be applied to the design of resource allocation algorithm for VANETs. Performance evaluation is conducted to verify the accuracy of our analysis.

Keywords: VANETs · Utility function · Best effort traffic · Real time traffic · pdf

1 Introduction

The tremendous advances in vehicular technologies has led to large amount of multimedia and data traffics in addition to the traditional traffic in Vehicular Ad Hoc Networks (VANETs). In order to improve the network efficiency and user experience, it is necessary to transmit different kinds of traffic simultaneously in VANETs. However, due to the performance requirements for different traffic is various in VANETs, resource allocation for multi-traffic is a challenging topic which has drawn lots of attention.

When the utility theory is introduced to describe the degree of user satisfaction, the complexity of resource allocation algorithm can be reduced. The utility function is measured on the basis of allocated resource (e.g., bandwidth, transmission rate), which is a non-decreasing function with respect to the given amount of resource [1]. In general, the more resource is allocated to user, the more satisfaction will be achieved.

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With the development of VANETs, the traffic evolves toward mixed one. Different performance requirement for various traffics can be represented as different utility function. The various traffic could be divided into two categories in VANETs. The first one is the best effort traffic which does not have strict quality of service (QoS) requirement, such as multimedia content downloading without delay restrictions. The other one is the real time traffic with strong QoS requirement, like on-line game, or interactive media.

Most of the research (e.g., [1–6]) on utility uses a simple proportion value to represent the channel quality. While the mobility model for VANETs is almost not been considered. They are not applied to the traffic in practical system for VANETs. Meanwhile, due to the high mobility of vehicles and the rapid change of network topology, it is a very challenging task to accurately describe the utility function for the traffic in VANETs, which is an important metric to evaluate the degree of user satisfaction.

To address these issues, we focus on the characteristics of utility function for different traffic in VANETs. The contributions of this paper are two twofold. First, we use Poisson process model to model the mobility characteristics of the vehicles in VANETs, which is more realistic and suitable for VANETs scenario. We also applied the path-loss model to describe the channel's condition. Second, according to the theoretical analysis proposed in this paper, the conditional probability density function (pdf) of utility function for different traffic in VANETs can be deduced, which is much easier to applied to the design of resource allocation algorithm for VANETs.

The rest of this paper is organized as follow. In Sect. 2, we summarize the related work in utility analysis. Section 3 proposes the considered network scenario and channel model. The details of theoretical analysis for traffic-aware utility function in VANETs is presented in Sect. 4. Section 5 investigates the numerical and simulation results to verify the analysis. The conclusion of this paper is drawn in Sect. 6.

2 Related Work

The research on utility in wireless networks has obtained a few achievements, including utility-based resource allocation and utility-based data dissemination. The utility-based resource allocation in wireless networks was studied in [1,2], the authors considered two types of traffic in the wireless networks and three resource allocation schemes were proposed. [6] adopted a resource allocation which was based on the unified utility function, and the channel was indicated by Signal to Interference plus Noise Ratio (SINR).

The utility function for different traffic was discussed in [4]. [5] proposed a data dissemination approaches, which is aiming to improve the system efficiency by introducing utility. The utility based relay vehicle selection algorithm was studied in [6]. We can see that either the resource allocation or the data dissemination can be used as the objective to explore the utility. To the authors' best knowledge, the practical channel model and realistic mobility model for VANETs almost not been considered in the previous work.

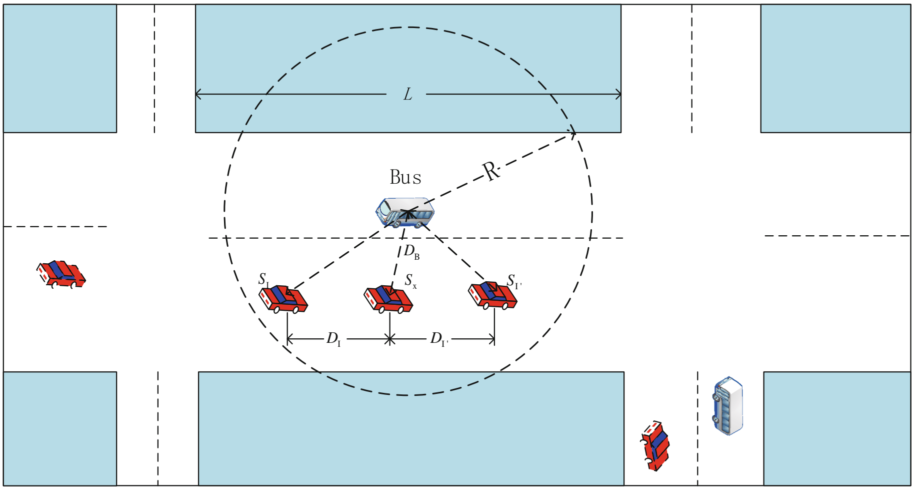

Fig. 1. Network scenario of traffic-aware utility based content downloading

3 System Model

3.1 Network Scenario

In this paper, we consider an application scenario for VANETs which is consisted of buses and sedans. We consider a bus B_P driving along an unidirectional road segment L by a constant speed to provide downloadable contents to its nearby sedans, which is shown in Fig. 1. Each vehicle is assumed to be equipped with a wireless device by which it can communicate with other vehicles within its communication range R. There is a link between a sedan S_X and the bus B_P when they are within the communication range of each other. However, one sedan's downloading procedure might be affected by other sedans. Due to the space limit, only the interferences from the closest sedans are considered in this paper. As shown in Fig. 1, the sedan S_I and $S_{\mathrm{I}'}$ are interference sedans for sedan S_X. As denoted in the figure, the two closest interference signals' transmission distance are marked as D_I and $D_{\mathrm{I}'}$, respectively. The distance between bus B_P and sedan S_X is denoted as D_B.

To model the sedans' mobility, it is assumed that the sedans enter the highway according to the Poisson process with intensities λ. Based on traffic flow theory [7], the velocity v of a vehicle can be expressed as $v = \lambda/\rho$, where ρ is the traffic density of the target highway scenario, the average number of vehicles within per unit length of the highway (vehicles per metre), and λ is the observed Poisson process density. According to the characteristic of Poisson process, the sedans' arrival time interval T should follow an exponential distribution with parameter λ. Hence, the pdf of T can be given as

$$f_T(t) = \lambda e^{-\lambda t}, (t \geq 0). \tag{1}$$

So the pdf of the distance between the interference sedan s_{I} and the sedan s_{x} can be represented as

$$f_{D_{\mathrm{I}}}(d) = \frac{\lambda}{v_{\mathrm{I}}} e^{-\lambda \frac{d}{v_{\mathrm{I}}}}, (d \geq 0). \tag{2}$$

where v_{I} is the average moving velocity of the sedan S_{I}. The distance $D_{\mathrm{I}'}$ follows the same distribution.

3.2 Channel Model

In this paper, we assume all vehicles send out the contents with identical transmission power P_{t} and the commonly used path-loss model is applied here to describe the signal power's attenuation:

$$P_{\mathrm{r}}(d) = \frac{P_{\mathrm{t}} G}{d^{\beta}}. \tag{3}$$

where $P_{\mathrm{r}}(d)$ is the average signal power at distance d from the base station, G is a constant which depend on the characteristics of radio transceivers, and β is the path loss exponent. Since fading gain of small scale fading changes over much smaller timescale, and in a frequency selective channel (such as one using OFDM) can be averaged or mitigated in the frequency domain [8], we assume that it does not impact transmission performance.

4 Theoretical Analysis

4.1 The Analysis for Transmission Rate

Theorem 1. *Let X be a continuous random variable having probability density function f_X. Suppose that g(x) is a strictly monotonic (increasing or decreasing), differentiable (and thus continuous) function of x. Then the random variable Y defined by $Y = g(X)$ has a probability density function given by*

$$f_Y(y) = \begin{cases} f_X[g^{-1}(y)] \left| \frac{d}{dy} g^{-1}(y) \right| & if\ y = g(x)\ for\ some\ x \\ 0 & if\ y \neq g(x)\ for\ all\ x \end{cases} \tag{4}$$

where g^{-1} is defined to equal that value of x such that $g(x) = y$.

According to the system model and the previous Lemma, the pdf of S_{I}'s interference power could be presented as

$$f_{Z_{\mathrm{I}}}(z) = f_{D_{\mathrm{I}}}(\sqrt[\beta]{\frac{P_t G}{z}}) \cdot \left| \frac{d}{dz} \sqrt[\beta]{\frac{P_t G}{z}} \right|, \tag{5}$$

which could be easily obtained the pdf of $f_{Z_{\mathrm{I}'}}$. Hence, the total interference power accumulated at sedan S_{X} is the sum of two independent random variables, as

$$f_{Z_{\mathrm{I+I}'}}(z) = \int_0^{\infty} f_{Z_{\mathrm{I}}}(z-y) \cdot f_{Z_{\mathrm{I}'}}(y) \mathrm{d}y. \tag{6}$$

The SIR at sedan S_{X} is the ratio of two random variables when the distance D_{B} is given. Then the conditional pdf could be presented as

$$f_{\text{SIR}}(s) = f_{Z_{\text{I+I}'}}(\frac{P_{\text{B}}}{s}|d_{\text{B}}) \cdot \left|\frac{d}{ds}(\frac{P_{\text{B}}}{s})\right|, \tag{7}$$

where $P_{\text{B}} = P_{\text{t}}G/d^{\beta}$.

Based on above analysis and Shannon theorem, the transmission rate in bps of the sedan when the bandwidth is B Hz

$$R = B\log_2(1+s). \tag{8}$$

Therefore, the conditional pdf of transmission rate R_{X} for sedan S_{X} is given as

$$f_{R_{\text{X}}}(r|d_{\text{B}}) = f_{\text{SIR}}(2^{\frac{r}{B}} - 1|d_{\text{B}}) \cdot \left|\frac{d}{dr}(2^{\frac{r}{B}} - 1)\right|. \tag{9}$$

where B is the bandwidth allocated to the traffic.

4.2 Utility Function Modeling

In VANETs, more and more studies focus on "user satisfaction" for resource allocation to avoid such a "throughput-fairnes" dilemma. We use the utility function $U(r)$ to describe the degree of user satisfaction, which is a non-decreasing function with respect to the amount of transmission rate R. However, as VANETs evolve, the traffic evolves toward a mixed one. As a result, classification of user data in terms of traffic type is required to effectively achieve the differentiated QoS performance [4]. In general, the types of traffic in VANETs could be roughly classified into two categories [6]. The utility function has various characteristics according to different traffic.

Best Effort Traffic: For best effort traffic, such as data traffics without hard delay requirement, the utility function should be steadily increasing with the growing transmission rate. When the transmission rate is small, the utility increases significantly with transmission rate. While the transmission rate is large enough, the degree of increment will keep decreasing. In summary, the utility function for best effort traffic should be a convex function according to the transmission rate.

Therefore, the utility function for best effort traffic could be obtained as

$$U_{\text{BE}}(r) = 1 - e^{\frac{k_1 \cdot r}{A}}. \tag{10}$$

where A, k_1 can be used to adjust the slope of the utility curve. The utility function for best effort traffic is shown in Fig. 2. In this paper, the form of utility function is refer to [1,6].

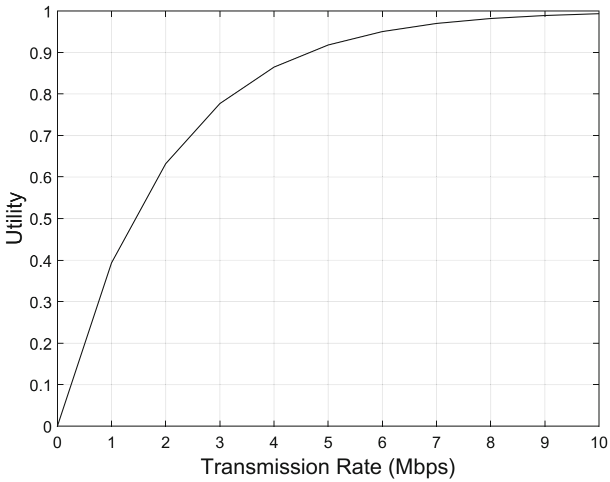

Fig. 2. Utility function of best effort traffic

Based on the analysis in subsection A, the conditional pdf of best effort traffic's utility function can be presented as

$$f_{U_{\mathrm{BE}}}(u|d_{\mathrm{B}}) = f_{R_{\mathrm{X}}}(\frac{A}{k_1}\ln(1-u)|d_{\mathrm{B}}) \cdot \left|\frac{d}{dr}(\frac{A}{k_1}\ln(1-u))\right|. \tag{11}$$

Then the cumulative distribution function (CDF) of utility function for a best effort traffic is

$$F_{U_{\mathrm{BE}}}(u|d_{\mathrm{B}}) = \Pr\{U_{\mathrm{BE}}(r) < u\} = \int_0^u f_{U_{\mathrm{BE}}}(t|d_{\mathrm{x}})\mathrm{d}t. \tag{12}$$

Real Time Traffic: For the real time traffic, such as streaming media traffic with guaranteed QoS requirements, the utility function should be a monotonically increasing function with the growing transmission rate. Due to the characteristics of real time traffic, the QoS requirement need certain resource to satisfy this requirement. The higher transmission rate allocated to the traffic plays a greater role in improving utilities when the transmission rate obtained by the traffic is less than the critical value. Whereas the transmission rate obtained by the traffic exceeds the critical value, the utility will be gradually decreased in increments. In general, the utility function for real time traffic should be a sigmoid function respect to the transmission rate.

Therefore the utility function for real time traffic could be presented as

$$U_{\mathrm{RT}}(r) = \frac{1}{1+e^{-k_2(r-r_0)}}. \tag{13}$$

where the parameter k_1 is used to adjust the slope of the utility curve around r_0. It reflects the characteristics of different real time traffic. The larger r_0 is,

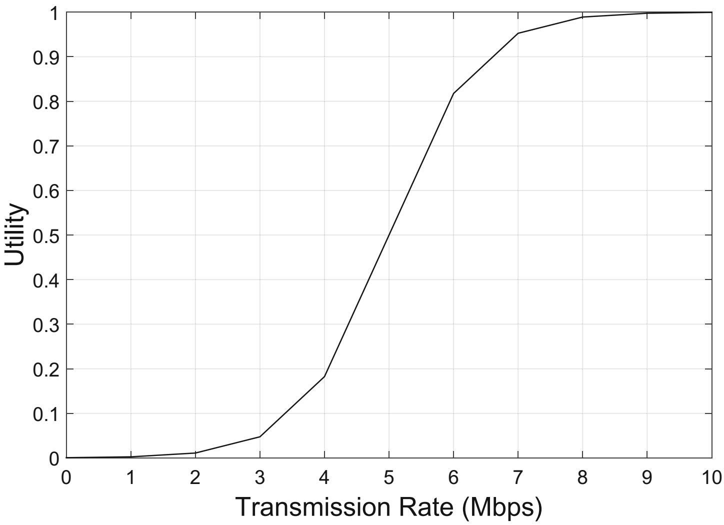

Fig. 3. Utility function of real time traffic

the more transmission rate should be allocated to the traffic to guarantee the QoS requirements. The utility function for real time traffic is shown in Fig. 3, where $r_0 = 5\,\text{Mbps}$.

Given the $f_{R_\text{x}}(r|d_\text{B})$, the conditional pdf of real time traffic's utility function can be obtained as

$$f_{U_\text{RT}}(u|d_\text{B}) = f_{R_\text{x}}(-\frac{1}{k_2} \cdot \ln(\frac{1}{u} - 1) + r_0|d_\text{B}) \cdot \left| \frac{d}{dr}(-\frac{1}{k_2} \cdot \ln(\frac{1}{u} - 1) + r_0) \right|. \quad (14)$$

Then the CDF of utility function for a real time traffic is

$$F_{U_\text{RT}}(u|d_\text{B}) = \Pr\{U_\text{RT}(r) < u\} = \int_0^u f_{U_\text{RT}}(t|d_\text{B})\text{d}t. \quad (15)$$

5 Numerical and Simulation Results

To verify the analysis results, a series of simulations has been conducted with Matlab. The Nakagami fading model is utilized with different fading factors, and the value of pathloss exponent β is selected by referring to a vehicular communication-based filed test result [9] as 3.18. The other major parameters for simulation are shown in Table 1. In the following part of this section, the simulation results are demonstrated in groups to show the effect of different parameters on the conditional pdf for utility function.

5.1 Impact of d_X on Conditional pdf for Utility Function

Intuitively, decreasing the distance between the sedan S_X and the resource pool B_P could support higher transmission rate with the same given bandwidth.

Table 1. Reference value for main parameters

Parameter	Description	Value
β	Pathloss exponent of the fading model	3.18
k_1	The slope parameter of the utility function for the best effort traffic	0.08
k_2	The slope parameter of the utility function for the real time traffic	0.05
P_t	The vehicular transmission power	400 mw
λ	The intensity of Poisson process	0.8
ρ	The traffic density of the target highway	0.15

In Fig. 4, the conditional pdf of utility function for best effort traffic is illustrated with different d_{B}, while the allocated bandwidth for the traffic is 1 MB. Generally, when the signal propagation distance is increased, the probability for sedan to obtain a high utility is decreased, which is mainly due to the obvious decrease of the received signal power. Moreover, it is hard to get a high utility when the bandwidth is limited. This is because that, for the best effort traffic, the utility function is steadily increasing with the growing transmission rate which is mainly decided by the allocated bandwidth and the SIR.

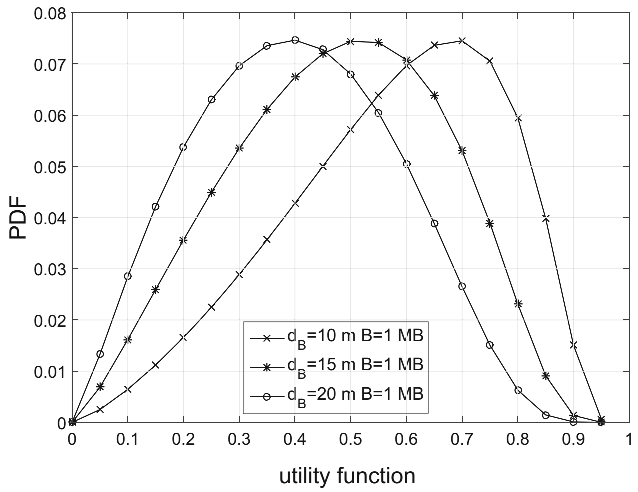

Fig. 4. Conditional pdf of utility function for best effort traffic with different d_{x}

Figure 5 compares the impacts of the different d_{B} on the performance of utility function for real time traffic. Generally, the probability is decreased with the increased utility value. Moreover, when the d_{B} is increased, the probability

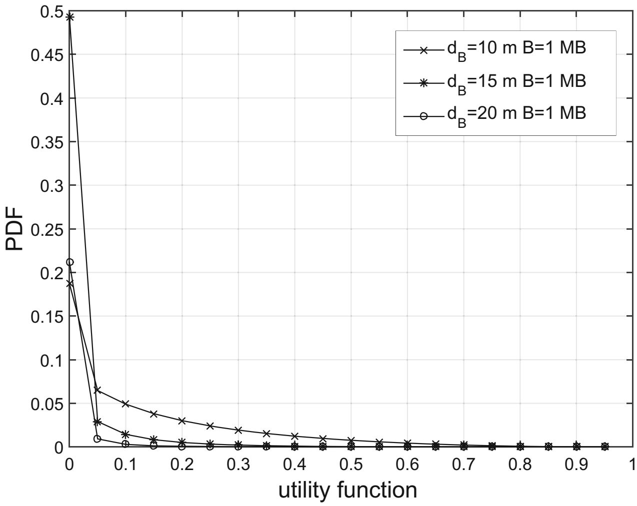

Fig. 5. Conditional pdf of utility function for real time traffic with different d_x

for the real time traffic to obtain a high utility value is decreased. This is mainly due to the fact that, the increased d_B decreases the probability for a higher SIR. As described earlier, the utility function for real time traffic is a sigmoid function respect to the transmission rate. Therefore, when the utility value is ranging from 0.1 to 0.9, the fluctuation of the pdf is not large, which is because of the limited bandwidth.

Therefore, once the bandwidth is given, we could make use of the analysis results fore utility function to design the resource allocation algorithm. For example, when d_B is 20 m, the probability for effort best traffic and real time traffic to obtain a high utility is extremely low. Therefore, in order to achieve the maximum network throughput, the network should allocate the resource to other sedans which have a shorter distance between the sedan and the bus.

5.2 Impact of B on Conditional pdf for Utility Function

For demonstrating the impact of B on conditional pdf for utility function, the SIR's conditional pdf is depicted with different given bandwidth in Figs. 6 and 7. The conditional pdf of utility function for best effort traffic is illustrated in Fig. 6. For the best effort traffic with larger allocated bandwidth B, the probability for the sedan S_X to have a high utility value is increased. This could be explained as that the increased B will increase the transmission rate, which is represented as the rise of utility value.

Finally, the conditional pdf of utility function for real time traffic is illustrated in Fig. 7 with different B. In general, when B is increased, the probability for the best effort traffic to obtain a high utility value is decreased. According to the figure, when utility value is increased from 0 to 0.1, the probability is

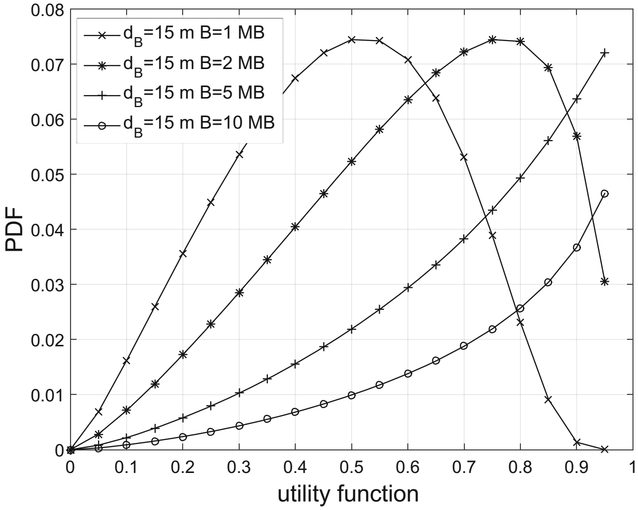

Fig. 6. Conditional pdf of utility function for best effort traffic with different B

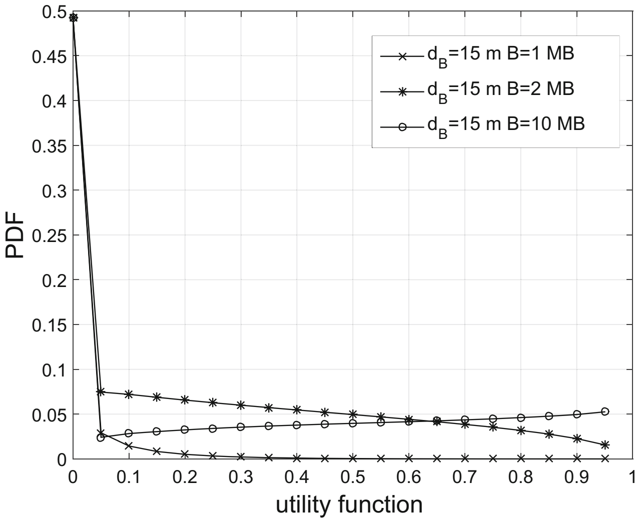

Fig. 7. Conditional pdf of utility function for real time traffic with different B

decreased slightly, which is mainly due to the characteristics of the real time traffic. The utility function for real time traffic is a sigmoid function respect to the transmission rate, which has a significantly increasing round a critical value of transmission rate.

Therefore, we could develop the resource allocation algorithm based on the above simulation results of utility function when the d_{B} is known.

6 Conclusion

In this paper, we analyzed the conditional probability density function (pdf) of utility function for different traffic in VANETs, which is based on Poisson process and the traffic flow theory. The stochastic characteristic of the utility value observed at a sedan was derived under the realistic channel model and mobility model. We believe this work will provide useful sights for the design and optimization of the source allocation with the help of utility function. Using the similar method, we plan to study the performance of utility function with the more realistic mobility model for VANETs, which could describe the spacial constrain revealed in the actual vehicular movement. These will be the follow-on work for this paper in the near future.

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