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Stochastic Delay Analysis of an Architecture Integrating VANET with LTE Networks

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***Abstract*—The communication delay, which has great impact on vehicle-to-infrastructure (V2I) networks, faces a large challenge on account of complex network topology. In this paper, a novel architecture that integrates LTE networks with IEEE 802.11 based Vehicle Ad Hoc Networks (VANETs) is proposed, due to their high data transmission rates and wide coverage area, respectively. The proposed scheme aims at delay analysis, which is under stochastic network calculus. The service rate of LTE wireless channels is modeled as a Markov modulation process by the mobility process of vehicles, and the behavior of IEEE 802.11 communication is characterized by a service model with the derived single packet access delay. Based on the analytical principle of stochastic network calculus, the stochastic delay upper bounds of V2I communication networks are derived via the Moment Generating Function (MGF) method. Finally, analytical and simulation results are utilized to validate the accuracy of the proposed model.**

I. Introduction

The rapid development of mobile society has made it possible to provide infrastructure, platform and Internet connectivity as communication services for the moving vehicles via wireless connection. Vehicles are equipped with on-board-unit (OBU) in the vehicle-to-infrastructure (V2I) communications [1]. This development has emerged new paradigm known as Vehicle Ad Hoc Networks (VANETs) [2]. To a large extent, VANETs have extended the horizon of drivers and on-board devices, and improved the road safety and traffic efficiency.

However, due to the high mobility and complex topology of vehicular networks, the quality of service (QoS) provided to the passengers on high-speed vehicles may be far from satisfactory. Therefore, it is important to design an applicable communications architecture while addressing the specific challenges of high speed environment and tightened QoS requirement. To fully exploit the potential of vehicular networks, plenty of literatures have focused on solutions to these issues. The work in [4] builds an one-dimensional Markov model to analyze the performance of periodic broadcast in VANETs, while in [1], authors have proposed an analytical model based on two-dimensional Markov Chain to evaluate the throughput performance in high speed V2I communications. Reference [5] focuses on the analysis of the QoS performance with the enhanced distributed channel access mechanism of IEEE 802.11p in vehicular networks.

In this paper, we propose a novel architecture for the organization of vehicular networks to evaluate the QoS performance. To improve the short-range and short-lived connectivity offered by IEEE 802.11, our system model integrates the existing 802.11 based VANET with LTE Wireless Networks. Benefiting from the large coverage area, high penetration rate, and high-speed terminal support in LTE networks [3], this architecture can provide an opportunity to offer efficient and QoS-guaranteed communication service to vehicular devices.

The analytical framework of proposed integrated system is based on stochastic network calculus. The network calculus is a theory of queuing systems for performance guarantee analysis. It facilitates the efficient derivation of backlog and delay bounds applying upper envelopes on traffic arrivals and lower bounds on the offered service, so called arrival and service curves [6]. The theory provides a rich variety of probabilistic traffic models based on moment generating function (MGF). A stochastic network calculus with MGF to evaluate performance in wireless networks was proposed in [7] and [8]. This paper focuses on stochastic delay analysis of proposed system framework.

The rest of this paper is structured as follows. Section II introduces system model including VANET and LTE Integrated architecture and the stochastic network calculus basics. In Section III, the stochastic service curves for both LTE fading channel and IEEE 802.11 channel are derived, respectively. Section IV presents and discusses the numerical and simulation results. Section V concludes the paper.

II. System Model

A. Architecture Description

The topology of our envisioned integration of IEEE 802.11 based VANET and LTE is portrayed in Fig.1, considering a scenario that each vehicle is picked up into one corresponding cluster and has transmission to the eNodeB via its own cluster. In this scenario, both LTE and IEEE 802.11 interfaces are equipped and activated by all the vehicles [9], and each vehicle transmits packets periodically. The VANET region is under the coverage of an eNodeB.

In each cluster, one vehicle is chosen as vehicle head (VH), and other vehicles are cluster members (see Fig.1) [2].

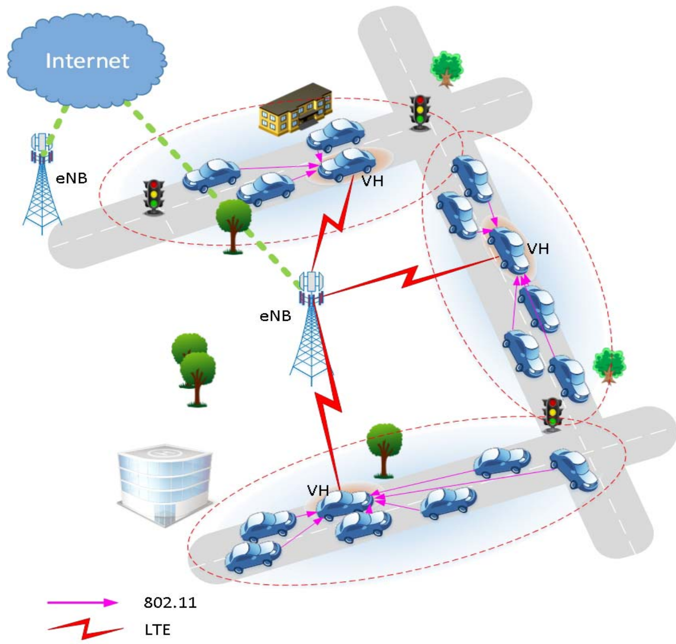

Fig. 1. System model.

The transmission among each cluster takes place only via 802.11 (assuming the direction and velocity of vehicles in one cluster are the same). All vehicles have the probability to be elected as VH, and VHs have the responsibility to gather all the packets transmitted by vehicles in their cluster and send them to the eNodeB via LTE wireless channels. Therefore, communication over this architecture is multi-hop, i.e., the transmission between the vehicles and their corresponding VHs via IEEE 802.11, and the transmission between VHs and the eNodeBs via LTE.

Fig.1 depicts a simplified view of the LTE communication network. LTE eNodeBs are located along the road to provide a seamless communication coverage. The clusters are connected to eNodeBs via wireless channels, while the eNodeBs are connected to the Internet via wireline links.

Communication among a cluster uses 802.11 protocols, in which distributed coordination function (DCF) is the fundamental mechanism. This random access scheme is based on the carrier sense multiple access with collision avoidance (CSMA/CA) protocol, and adopted an exponential backoff scheme [10]. Each vehicle should sense the channel idle for an interval of distributed interframe space (DIFS) when having a packet to transmit. If the channel is busy, the access should be deferred. Then, a backoff time uniformly chosen in the range $(0, CW_k - 1)$ is initiated, where the contention window CW_k is first set by CW_{min} and doubled after unsuccessful transmission, up to the maximum value $CW_{max} = 2^M CW_{min}$. The backoff counter is decremented by 1 after a time slot, and is frozen whenever the channel is sensed busy. The vehicles will attempt to access to the VH when the counter reach zero, and the retransmission times cannot be greater than K. In order to reduce the collision duration, we use the RTS/CTS mechanism, i.e., transmitting data packet after a successful exchange of RTS and CTS packets.

B. Stochastic Network Calculus

In this subsection, we provide a brief introduction into some relevant concepts and principles of stochastic network calculus and make some assumptions corresponding to our system model.

For each node, we describe the arrival and departure processes as real-valued cumulative functions $A(0,t)$ and $D(0,t)$ respectively, which represent the arrivals and departures of a flow at/from a system in the interval of $(0,t]$. By definition, $A(0,t)$ and $D(0,t)$ are non-negative and non-decreasing in t, and we have $A(s,t) = A(0,t) - A(0,s)$ and $D(s,t) = D(0,t) - D(0,s)$. The backlog of the flow at time $t > 0$ is given by [11]

$$b(t) = A(0,t) - D(0,t), \tag{1}$$

and the delay of the flow is

$$d(t) = \inf\{\tau \geqslant 0 : A(0,t) \leqslant D(0,t+\tau)\}. \tag{2}$$

The service of the node in the time interval $(s,t]$ is given by a random process $S(s,t)$, which represents the cumulative amount of workload offered by the system. The system can be describes as a dynamic server which characterizes queue system in that

$$D(0,t) \geq \inf_{\tau \in [0,t]} [A(0,\tau) + S(\tau,t)]. \tag{3}$$

Due to the stationarity, $A(s, s+t)$ equals to $A(0,t)$ in distribution for all $s \geqslant 0$. Then we define the moment generating fuction (MGF) of $A(0,t)$ as follows [7]

$$\mathrm{M}_A(\theta,t) = E[e^{\theta A(0,t)}]. \tag{4}$$

For notation purposes, we also adopt $\overline{\mathrm{M}}_S(\theta,t) = \mathrm{M}_S(-\theta,t)$.

Theorem 1: Let $S_1(s,t)$ and $S_2(s,t)$ be two dynamic servers in tandem. Then, the service offered by the series can be described as an equivalent single server $S(s,t)$ with $S(s,t) = \inf_{\tau \in [s,t]} [S_1(s,\tau) + S_2(\tau,t)]$. Considering two service processes are both statistically independent, the MGF of the equivalent single server can be exploited from the two MGFs $\overline{\mathrm{M}}_{S_1}(\theta,t)$ respectively $\overline{\mathrm{M}}_{S_2}(\theta,t)$, and upper bounded by

$$\overline{\mathrm{M}}_S(\theta,t) \leq \sum_{\tau=1}^{t} \overline{\mathrm{M}}_{S_1}(\theta,\tau)\overline{\mathrm{M}}_{S_2}(\theta,t-\tau). \tag{5}$$

Theorem 2: Consider a dynamic server $S(s,t)$ with the stochastic arrival process $A(s,t)$. If $S(s,t)$ is independent of $A(s,t)$, then an upper backlog bound and an upper delay bound, which are violated at most violation probability $\varepsilon \in (0,1]$, are given by [6]

$$b = \inf_{\theta>0} [\frac{1}{\theta}(\ln \sum_{s=0}^{\infty} \mathrm{M}_A(\theta,s)\overline{\mathrm{M}}_S(\theta,s) - \ln\varepsilon)], \tag{6}$$

$$d = \inf_{\theta>0} \{\inf[\tau : \frac{1}{\theta}(\ln \sum_{s=\tau}^{\infty} \mathrm{M}_A(\theta,s-\tau)\overline{\mathrm{M}}_S(\theta,s) - \ln\varepsilon) \leq 0]\}. \tag{7}$$

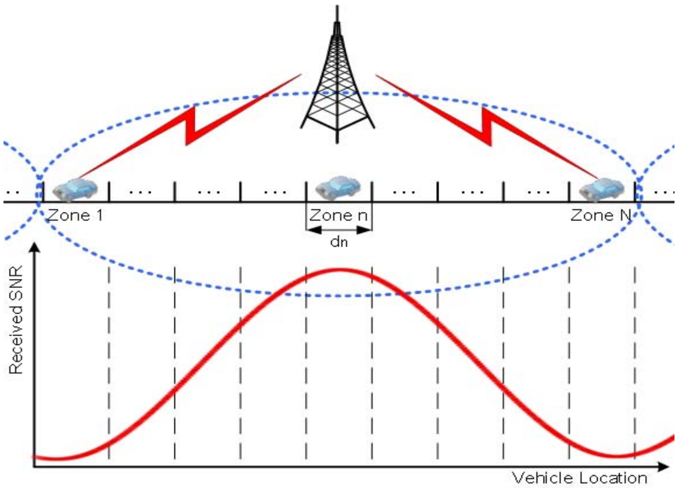

Fig. 2. LTE communication fading channel.

III. Stochastic Service Curve

In this section, we focus on the derivation of MGF stochastic service curves in the proposed multi-hop network, that is, the communication between VHs and the eNodeBs via LTE fading channel based on Finite State Markov Chain, and the communication between vehicles and their corresponding VHs via IEEE 802.11.

A. Finite-State Markov based Fading Channel

We divide the radio coverage of an eNodeB into multiple zones denoted as $\mathbb{Z} = \{1, 2, ..., N\}$, as shown in Fig.2, such that in each spatial zone n, $n \in \mathbb{Z}$, the average received SINR over fading channel between the eNodeB and each zone is supposed to be the same, denoted by $\overline{\gamma}_n$.

The mobility of vehicles is described as a Markov chain model shown in Fig.2, in which each state corresponds to one spatial zone [1]. The duration for which vehicles stay in each zone $n \in \mathbb{Z}$ is assumed to be geometrically distributed with mean time t_n, which is determined by the length of each zone d_n and the average velocity of vehicles v, as $t_n = d_n/v$. Within a small duration, e.g., T_f, vehicles either move to the next zone with probability T_f/t_n, or remain in the current zone with the rest probability $1-T_f/t_n$. If one vehicle leaves the current eNodeB and connects to a new one, it will be regarded to move from state N back to state 1, representing a new cycle of Markov chain.

Denote by $p_{n,m}$ and π_n the state transmission probability from state m to state n and the steady-state probability of state n in this Markov chain, respectively. Correspondingly, $\mathbf{P} \in \mathbb{R}^{N\times N}$ represents the transition probability matrix with $p_{n,m}$, $n, m \in \{1, ..., N\}$, and $\pi = [\pi_1, \pi_2, ..., \pi_N] \in \mathbb{R}^{1\times N}$ is the stationary state distribution vector. The stationary probability π_n is given by

$$\pi_n = d_n/D. \tag{8}$$

The state transition probability of Markov chain over one period T_f can be described as

$$p_{n,l} = \begin{cases} 1-T_f/t_n & \text{if } l = n \\ T_f/t_n & \text{if } n < N, l = n+1 \text{ or } n = N, l = 1 \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

The instantaneous SINR, denoted by $\gamma_n(\mathrm{t})$, is observed at the receiver in each zone n, which is affected by both large-scale fading and fast fading. Due to the large fading rate $f_D\Delta T$ caused by high mobility velocity of the vehicles, $\gamma_n(\mathrm{t})$ is an i.i.d. random variable over disparate time slots. Considering the multipath fast fading description as a Rician fading channel model, we have $\gamma_n(\mathrm{t}) = \overline{\gamma}_n|h(t)|^2$, where $|h(t)|$ is the fading gain with Rician distribution at time t. Therefore, the instantaneous, information-theoretic channel capacity over the wireless channel $r_n(t)$ in zone n can be represented by the Shannon formula as $r_n(t) = C\log(1+\gamma_n(t))$, where C is a constant. Let $\mathbf{V}(\theta)$ denote the channel capacity diagonal matrix, so we have [7]

$$\mathbf{V}(\theta) = \mathrm{diag}(e^{\theta r_1}, e^{\theta r_2}, ..., e^{\theta r_N}) \in \mathbb{R}^{N\times N}. \tag{10}$$

Summarizing the above discussions, the MGF of the corresponding stochastic service process $S_1(t)$ for all $t \geq 0$ and all $\theta > 0$ can be derived as

$$\overline{\mathrm{M}}_{S_1}(\theta, t) = \pi(\mathbf{V}(-\theta)\mathbf{P})^{t-1}\mathbf{V}(-\theta)\mathbf{1}_N, \tag{11}$$

where π and $\mathbf{P}$ are the matrices of steady-state probability and state transmission probability given in (8) and (9), and $\mathbf{1}_N$ denotes a column vector with all N elements being one.

B. Stochastic Service Curve of 802.11 Protocol

In this subsection, we derive a service model to analyze the access process from the vehicles to VH via IEEE 802.11, which facilitates applications of the stochastic network calculus.

Assuming that there are L vehicles as cluster members in one cluster, they attempt to transmit an packet with probability of p_a. We focus on one tagged vehicle, and then the collision probability that at least one non-tagged vehicle transmits at the same time slot, denoted by p_c, can be derived by $p_c = 1-(1-p_a)^{L-1}$ [12].

Let $H = L_{PHY} + L_{MAC}$ be the packet header, L_P be the packet length, and R_P be the transmission rate. Then the period of successful transmission T_s equals to

$$T_s = \frac{H+L_P}{R_P} + RTS + CTS + 3SIFS + ACK + DIFS. \tag{12}$$

And the period of collision T_c equals to

$$T_c = RTS + DIFS. \tag{13}$$

In the IEEE 802.11 network, the access delay is represented by a random variable, denoted by D, which includes the delay by C caused by unsuccessful transmissions of the tagged vehicle, the sum of durations by B of backoffs of the tagged vehicle with collisions and successful transmissions involving the non-tagged vehicles, and the interval of the final successful transmission. Therefore, the access delay D can be expressed as [13]

$$D = C + B + T_s. \tag{14}$$

Obviously, the value of C strongly depends on the number of retransmissions. Let P_i be the probability that a successful transmission happens at the ith retransmission, then P_i is given by [12]

$$\begin{cases} P_i = (1-p_c)p_c^i, & i \in \{0, 1, ..., K-1\} \\ P_K = p_c^K. \end{cases} \tag{15}$$

The probability mass function (PMF) of C is

$$P\{C = i \cdot T_c\} = P_i, \quad i \in \{0, 1, ..., K\} \tag{16}$$

In the backoff process, if the channel is idle with probability of $1 - p_c$, the backoff counter will be decremented by 1 for one time slot, denoted by σ. When detecting an ongoing successful transmission with probability of P_{suc}, the backoff counter will be deferred by a period of T_s, while if there is any collision among the non-tagged vehicles, the deferring time will be T_c. P_{suc} implies there is only one non-tagged vehicle transmitting, so P_{suc} can be given by

$$P_{suc} = (L-1)p_a(1-p_a)^{L-2}. \tag{17}$$

Therefore, the duration for which the counter is decreased by 1, denoted by T_b is obtained:

$$T_b = (1-p_c) \cdot \sigma + P_{suc} \cdot T_s + (p_c - P_{suc}) \cdot T_c. \tag{18}$$

Combining the above results together, the mean $E[D]$ of the access delay is found as

$$\begin{aligned} E[D] &= E[C] + E[B] + T_s \\ &= T_c \cdot \sum_{i=1}^{K} p_c^i + T_b \cdot \sum_{i=1}^{K} \mu_i p_c^i + T_s, \end{aligned} \tag{19}$$

where μ_i is the mean of the backoff intervals at the ith backoff stage.

For the case of constant length data packets, we model the 802.11 process as a periodic access service process, whose access period is the mean delay $E[D]$. For all $t \geq 0$ and all $\theta > 0$, it is known, see [15], that

$$\overline{\mathrm{M}}_{S_2}(\theta, t) = e^{-\theta L_P \lfloor \frac{t}{E[D]} \rfloor}[1+(\frac{t}{E[D]} - \left\lfloor \frac{t}{E[D]} \right\rfloor)(e^{-\theta L_P} - 1)], \tag{20}$$

where L_P is the constant length of one packet.

The MGFs of two dynamic service processes in tandem are derived above in (11) and (20), therefore, the upper bound of the MGF of the equivalent service process $\overline{\mathrm{M}}_S(\theta, t)$ can be trivially obtained with (5).

IV. Numerical and Simulation Results

In this section, both simulation and numerical results are presented to evaluate the delay performance of the proposed vehicular communication architecture.

The system parameters are given in Table.I, while the IEEE 802.11 transmission parameters used here are from the extensive measurements reported in [12]. We adopt the D2a sub-scenario channel model of Winner Phase II for LTE moving channel [14]. By default, the velocity of vehicles is constant as 20 m/s. The whole road section is divided into 10 spatial zones as specified in Table.II based on the average SINR at different zones.

TABLE I
System Parameters

Parametres	**Values**
Time units	1 ms
Packet Length	1000 bytes
eNodeB Coverage	1500 m
Transmit power of vehicle	23 dBm
Bandwidth	3 MHz
Carrier frequency	1.9GHz

TABLE II
Parameters of Zones

Zone	1&10	2&9	3&8	4&7	5&6
Length (m)	300	200	100	100	50
$\overline{\gamma}$ (dB)	11.457	16.807	21.825	27.230	32.097

For simplicity, we assume a periodical arrival process with the same parameters to each vehicle. The vehicle generates G packets at times $\{I\tau + n\tau, n = 0, 1, ...\}$, where τ is the period of the source and I is the initial start time which is uniformly distributed over the interval $[0, 1]$. For all $t \geq 0$ and $\theta \geq 0$, the MGF of the arrival process is given by [15]

$$\mathrm{M}_A(\theta, t) = e^{\theta G \lfloor \frac{t}{\tau} \rfloor}[1 + (\frac{t}{\tau} - \left\lfloor \frac{t}{\tau} \right\rfloor)(e^{\theta G} - 1)]. \tag{21}$$

Our simulation program is built on the MATLAB platform. Each vehicle has its own buffer, where the arrival packets wait for transmission. Delay bounds are computed using the stochastic network calculus shown in Sect. II.

We first evaluate the case that each cluster has 10 vehicles. Fig.3 compares the analytical upper bounds and the simulation results under violation probabilities $\varepsilon \in [10^{-7}, ..., 10^{-2}]$, where the burst size and period time are set as $G = 1$ packet and $\tau = 0.5$ s respectively. The relative error $d_{ana}/d_{sim} - 1$ is included in Fig.3, which shows a tight bound between the analytical bounds and the corresponding simulation results.

In Fig.4, we compare analytical bounds and simulation results under different packet arrival rates, where we set violation probability and the burst size to be $\varepsilon = 10^{-2}$ and $\tau = 0.5$ s, respectively, and change the values of G, resulting in different packet arrival rates by $\lambda_p = G/\tau$. The figure shows that, with increasing data arrival rate per vehicle, the delay increases as expected, which is due to the increase of system load.

For the comparison in Fig.5, we fix the packet arrival rate to be 2 and the violation probability $\varepsilon = 10^{-2}$, and investigate how the delay performs under different number of vehicles in one cluster. It is clear from the figure that the more vehicles there are, the longer the delay performs. This is attributed to

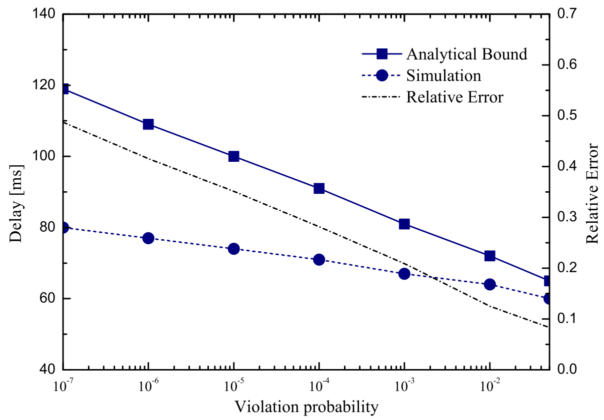

Fig. 3. Comparison of simulation and analytical results under different violation probabilities

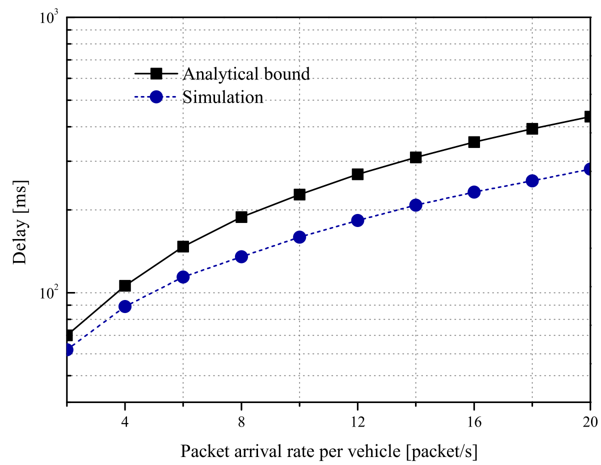

Fig. 4. Impact of packet arrival rate on delay performance

that, when the vehicles increase, the access delay to VH will correspondingly increase, and additionally, the system load of VH to transmit to eNodeB becomes larger. Again, Fig.5 demonstrates a close match between analytical bounds and simulation results.

V. Conclusion

In this paper, stochastic delay bounds of an architecture integrating IEEE 802.11 based VANET and LTE wireless channels are derived based on the analytical principle behind the stochastic network calculus. The service process of LTE fading channels is modeled as a Finite State Markov Chain, where both large-scale fading and small-scale fading are taken into consideration. The service process of 802.11 is assumed as a periodic model based on the access delay via CSMA/CA protocol. Both service curves are derived using the MGF methods. Based on the principle of stochastic network calculus, the delay upper bounds are obtained via the MGF methods. Numerical results and simulation results under various system parameter settings are presented and compared. The comparison indicates a good match between the analytical bounds and the simulation results, validating the analysis.

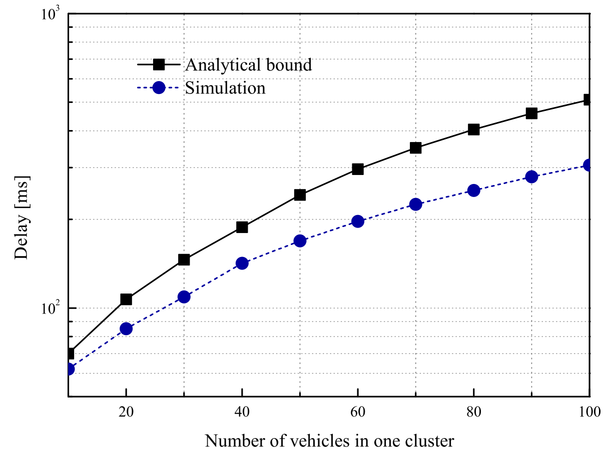

Fig. 5. Impact of vehicle numbers on delay performance

VI. Acknowledgment

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