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Performance Analysis of RSU Relaying in the Vehicular Network

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요 약

본 논문에서는 도심 교차로에서 자율주행차의 V2I(Vehicle to Infrastructure) 통신 링크 성능을 분석한다. 고속도로와 달리 도심 지역의 통신 전파는 차량 및 건물의 증가에 따라 영향을 받는다. 따라서 NLOS(None Line Of Sight) 상황을 피하기 위해 RSU 중계가 필요하다. RSU(Road Side Unit)는 교차로에 위치하며 모든 BSMs(Broadcast Safety Messages)은 RSU를 통해 중계되므로, 모든 차량이 LOS(Line of Sight) 상태가 될 수 있다. 기존 논문에는 도시 지역에서의 NLOS 상태를 피하기 위한 RSU 중계에 대한 성능 분석이 존재하지 않는다. 따라서 본 논문에서는 LOS 및 NLOS에 대한 RSU 중계 성능을 분석한다. 성능 분석을 위해 평균 시스템 시간과 평균 대기열 크기를 도출하고, 이 두 가지 관점에서 서비스 시간의 영향을 분석한다.

Key Words : RSU Relaying, V2I communication, Autonomous vehicle, Numerical analysis, Simulation

ABSTRACT

In this paper, we analyze the vehicle to infrastructure(V2I) communication link performance of autonomous vehicles at intersection in urban areas. Unlike highway, the propagation of communication is affected by an increase of vehicles and buildings in urban areas. Therefore, RSU relaying is necessary to avoid none line of sight (NLOS) situation. The road side unit (RSU) is located at the intersection, and all broadcast safety messages (BSMs) are relayed through the RSU. As a result, all vehicles can be in line of sight (LOS) status. In urban areas, there is no performance analysis for RSU relaying to avoid NLOS status. Therefore, we analyze the performance of RSU relaying for LOS and NLOS in vehicular networks. For performance analysis, mean system time and mean queue size are derived and analyzed for the impact of service time from these two perspectives.

Ⅰ. Introduction

Studies on autonomous vehicles have been actively carried out. The main goal of autonomous vehicles is to provide safety and efficiency on the road by communicating the necessary information in a timely manner[1]. Vehicular communication technologies, such as vehicle to everything (V2X), vehicle to vehicle (V2V), vehicle to pedestrian (V2P), and vehicle to infrastructure (V2I), allow vehicles to actively exchange information about their surrounding traffic. The information exchanged through Basic Safety Messages (BSMs) within a defined coverage area allows a considerable increase of road safety level[2]. The utilization of BSMs, containing a vehicle's information (location, speed, heading, etc), allows preventing collisions in a cooperative way.

Most studies on vehicle communication are analyzed and evaluated on highways, not in urban

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areas[2-4]. Unlike highways, communication propagation is affected by increasing vehicular density and buildings in urban areas. Therefore, the performance of communication links can be severely degraded in urban areas[1,5]. It can lead to accidents and dangerous conditions. In this regard, vehicular assisted relaying has been proposed to improve the performance of communication propagation[1,6]. But vehicular resources are not sufficient to process all BSMs. V2I communication by RSU has the ability to improve this situation.

As a suitable location for RSU, an intersection with a traffic signal controller was selected[7,8]. Therefore, all BSMs can be relayed by the traffic signal controller equipped with RSU at the intersection. In other words, not only the line of sight (LOS) but also the none line of sight (NLOS) are covered by the RSU. As a result, it helps to avoid being affected by communication propagation degradation.

We analyze the performance of the RSU when processing BSMs for all vehicles in NLOS and LOS situations. The analytical approach is applied to derive proper service time using different queue sizes and system times of an M/G/1 queuing model[9]. In addition, we simulated two different BSMs intervals and vehicle densities. Then, based on the numerical results, we propose a proper service time and queue size. The communication between the vehicle and the RSU is simulated using Network Simulator 3 (NS3) by selecting the proper service time in the numerical result.

The contributions of this study are as follows:

We analyze the performance of the RSU when processing BSMs in a vehicle communication scenario.

We suggest proper service time through performance analysis through simulation and modeling.

The remainder of this paper is structured as follows. Related work is discussed in Section II. A model for performance analysis of the RSU is mathematically formulated in Section III. In Section IV, simulation results and discussions are presented. Conclusion and a view on the future works are drawn in Section V.

Ⅱ. Related work

The autonomous vehicle aims to improve driving safety, driving comfort, and economy, and reduce traffic accidents. In this regard, information about the surroundings is obtained through V2X communication, including V2V, V2P, and V2I. In general, in V2X communication, V2V and V2I are the two systems that are mainly emphasized. Many studies have been conducted on the performance analysis of V2I and V2V communication links[1-6].

However, most of these studies are evaluated on highways[2-4]. Because of the complex environment in urban areas, V2V and V2I communication entail numerous challenges, such as communication link performance degradation[1,5]. In particular, the performance of communication link depends on the location of the vehicle, and when the positions of the vehicles are on the perpendicular street (NLOS state), the performance of communication link is degraded.

The vehicle assisted relaying was proposed to overcome this situation[1]. In the proposed method, the relay vehicle is selected autonomously, and the relay vehicle selectively rebroadcasts the BSMs. Two types of strategies using dedicated resources and dynamic resource relaying are evaluated through the packet delivery rate (PDR) analysis model. Furthermore, by using a multi-hop communication mode, the communication range of V2V can be significantly increased[6]. The performance of multi-hop V2V communication was analyzed considering the distance between the source and destination vehicle. As the transmission distance from the source to the destination increases, the number of multi-hops increases. Increasing the number of multi-hops makes resource allocation more complex. But vehicle resources are not sufficient. So, we select the RSU relay to put all vehicles into the LOS state at the intersection. In particular, we are interested in finding the system time of the RSU to process all the BSMs of vehicles within a certain range.

Ⅲ. System model

To analyze the average system time of the RSU, we apply the M/G/1 Queueing model[9]. The key notations adopted for this system model are shown in Table 1. The arrival rate of BSMs for a vehicle is given by λ. The subscript n represents the nth BSMs. As shown in Fig. 1, we set up an environment with a four way, four lane urban intersection that limited the region of interest (ROI) to the 300 m × 300 m area around the intersection. The intersection is selected as a suitable location for a traffic signal controller equipped with RSU[7,8].

In Fig. 1, V1 and V2 are on the same street, the communication link is LOS. On the other hand, V1 and V3 are on the perpendicular street, it is NLOS.

We need to calculate the time spent in the RSU, which means it is time required by the RSU when sending the BSMs from vehicle V1 to V2 or V3 via the RSU. The total time spent in system is denoted as T. The expected value of a variable T is $E[T]$.

The total time spent in the RSU can be defined as.

$$E[T] = E[W] + E[X] \tag{1}$$

And mean waiting time is given by.

$$E[W] = E[N_q] \times E[X] + E[U] \tag{2}$$

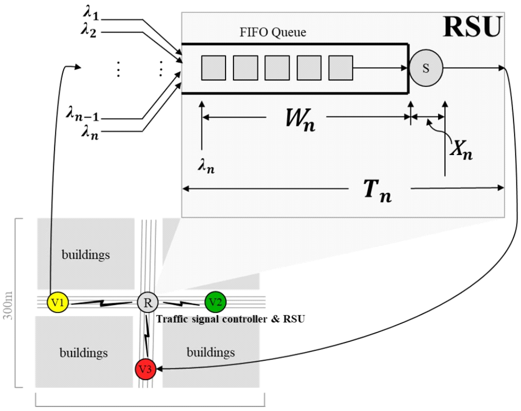

Fig. 1. Communication scenario

Table 1. Key notations for the system model

Notation	Semantics
N_q	Queue size of waiting message
U	Unfinished work in the server
W	Waiting time to wait for the service
X	Service time
λ	Arrival rate
T	System time
ρ	Utilization factor

The key observation is that the mean queue length $E[N_q]$ can be expressed in term of the waiting time by Little's result.

$$E[N_q] = \lambda E[W] \tag{3}$$

The utilization factor of RSU is given by

$$\rho = \lambda E[X] \tag{4}$$

Returning to (2) we apply (3), (4) to obtain.

$$\begin{aligned} E[W] &= \lambda E[W] \times \frac{\rho}{\lambda} + E[U] \\ &= \frac{E[U]}{1-\rho} \end{aligned} \tag{5}$$

Now, it remains to determine $E[U]$. According to the hitchhiker's paradox, the following equation is derived. $R(t)$ is the unfinished work in the server as a function of time. Consider a long interval of time t.

$$\begin{aligned} E[U] &= \frac{1}{t}\int_0^t R(t')dt' \\ &= \frac{1}{t}\sum_{i=1}^{n}\frac{1}{2}X_i^2 \\ &= \frac{n}{t} \times \frac{1}{n} \times \sum_{i=1}^{n}\frac{1}{2}X_i^2 \end{aligned} \tag{6}$$

$\frac{n}{t}$ is determined by the arrival rate λ and $\frac{1}{n} \times \sum_{i=1}^{n}\frac{1}{2}X_i^2$ is $= \lambda\frac{1}{2}E[X^2]$. Therefore, the following equation is derived.

$$E[U] = \lambda \frac{1}{2} E[X^2] \tag{7}$$

Returning to (5), we apply (7).

$$E[W]= \frac{\lambda E[X]LSUP2}{2(1-\rho)} \tag{8}$$

Rewrite this result in terms of C_v^2, squared coefficient of variation for service time, the following equation (9) is derived.

$$C_v^2 = V[X] \,/\, E[X]^2 \tag{9}$$

$V[X]$ is a standard derivation of X. The standard derivation is given by

$$V[X]= E[X^2] + E[X]^2 \tag{10}$$

Thus, by relations (9) and (10), $E[X^2]$ is expressed as (11).

$$\begin{aligned} E[X^2] &= V[X] + E[X]^2 \\ &= (1+c_v^2) \times E[X]^2 \end{aligned} \tag{11}$$

Returning to (8) we apply (11) to obtain.

$$\begin{aligned} E[W] &= \frac{\lambda E[X^2]}{2(1-\rho)} \\ &= \frac{1+C_v^2}{2} \times \frac{\rho}{1-\rho} \times E[X] \end{aligned} \tag{12}$$

Now, we need to derive the time spent in the system which is derived by T. According to the definition of (1) and (12), (13) can be derived.

$$\begin{aligned} E[T] &= E[X] + \frac{1+C_v^2}{2} \times \frac{\rho}{1-\rho} \times E[X] \\ &= E[X] \times (1 + \frac{1+C_v^2}{2} \times \frac{\rho}{1-\rho}) \end{aligned} \tag{13}$$

In the case of constant service time, squared coefficient of variation has $C_v^2 = 0$. Therefore, the following (14), (15) can be obtained.

$$E[W]= \frac{1}{2} \times \frac{\rho}{1-\rho} \times E[X] \tag{14}$$

$$E[T]= E[X] \times (1+\frac{1}{2} \times \frac{\rho}{1-\rho}) \tag{15}$$

By applying Little's result (3), (16) can be obtained.

$$E[N_q]= \frac{\lambda^2 E[X^2]}{2(1-\rho)} \tag{16}$$

By applying (11).

$$E[N_q]= \frac{1+C_v^2}{2} \times \frac{\rho^2}{1-\rho} \tag{17}$$

Finally, the following (18) can be obtained.

$$E[N_q]= \frac{1}{2} \times \frac{\rho^2}{1-\rho} \tag{18}$$

Ⅳ. Simulation

In this section, we analyze the performance of the RSU from two main perspectives based on numerical results. First, we analyze the impact between the system time (T) and the service time (X). Then we examine the relationship between service time (X) and the limited queue size (N_q).

According to IEEE 802.11p protocol WAVE, BSMs intervals are recommended as 100 ms or 300 ms[10]. Periodic messages are generated every 300 ms to broadcast vehicular status. Emergency messages have to be broadcast and received within 100 ms. Therefore, V2I communication is simulated by setting the BSMs interval of 100 ms and 300 ms.

Assuming that the maximum vehicles exist at roughly 10 meter interval, the maximum vehicle number is 240. Markov chain is ergodic if ρ < 1 (we shall assume ρ < 1 below)[8]. Therefore, we assume that ρ < 1 only until the vehicle is 240.

Fig. 2 shows that service time (X) for each

BSMs interval when $\rho < 1$ in 240 vehicles. This service time is the result derived from equation (4). It also shows the system time for the vehicle when the corresponding service time is applied. When the BSMs interval is 300 ms and the service time is 1.245 ms, $\rho < 1$ is satisfied. It is satisfied when the service time is 0.4166 ms at BSMs interval of 100 ms. There is about a threefold difference between the two BSMs intervals. The system time increases dramatically when the utilization factor is close to 1. In other words, the system time rises exponentially with the number of vehicles. Therefore, the communicating for safety in all vehicles, should be less than the service time corresponding to the interval shown in Fig. 2.

Fig. 3 and Fig. 4 show the relationship between the system time (T) and the vehicle number when the system time is limited. The result of this system time is derived from equation (15). The service time is calculated after defining the maximum system time that the RSU can handle within 1, 2, and 3 sec, respectively. We have presented the proper service times given the limited system times according to the number of vehicles. If the service time is within 0.3333 ms, it is possible to process all vehicles within 1 sec at BSMs interval 100 ms. When the interval is 300 ms, the service time is set at 0.648 ms. If the system time is set to less than 1 sec, the difference between the two BSMs is about twice the difference, not three times the difference between them.

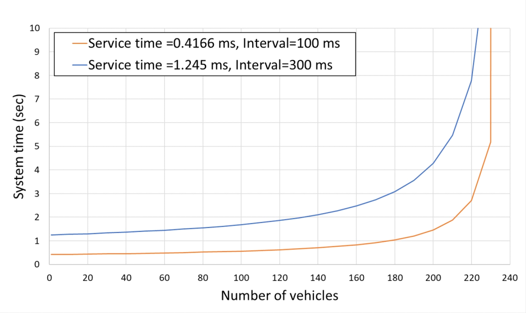

Fig. 2. System time according to BSMs interval

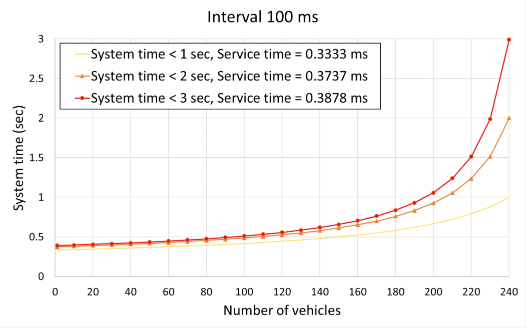

Fig. 3. Fixed maximum system time in BSMs interval 100 ms

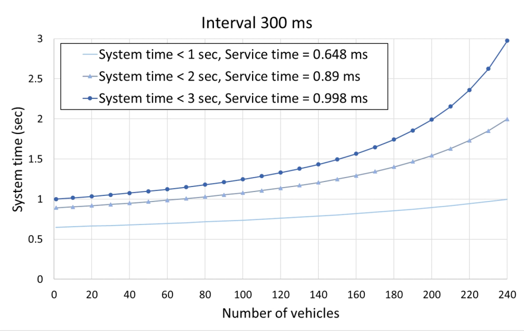

Fig. 4. Fixed maximum system time in BSMs interval 300 ms

In Fig. 5 and Fig. 6, we calculate the proper service time (X) with a limited queue size (N_q).

The relationship between this service time and queue is derived from equations (3) and (14). As shown in Fig. 5, if the queue length is fixed at 6 or less, all processing is possible when the service time is within 0.3867 ms. The slopes of the two BSMs intervals are different, but the trend lines are similar. In addition, the difference between the two BSMs intervals is three times the difference between them. However, the service time does not increase

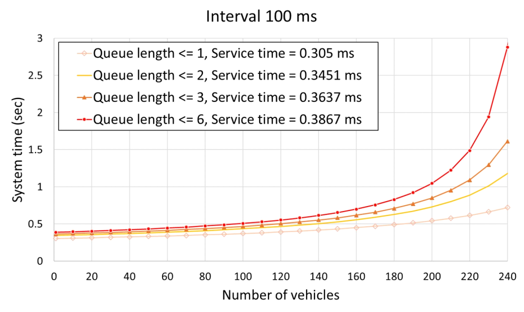

Fig. 5. Limited queue length in BSMs interval 100 ms

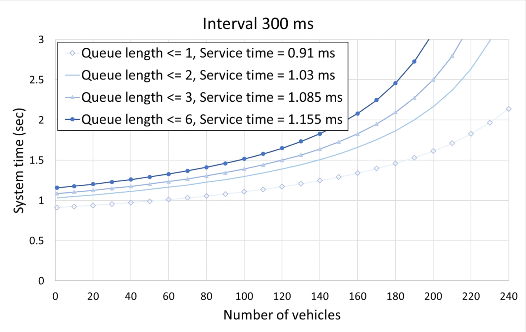

Fig. 6. Limited queue length in BSMs interval 300 ms

proportionally as the size of the queue length increases. In addition, an increase in the limited queue size, regardless of the interval, has a minor influence on service time.

We verify the RSU performance through an NS3 simulation. The parameters for simulation in NS3 are displayed in Table 2. With NS3 simulations, we examine the end-to-end delays of various vehicle numbers, including service times of RSU. First, we investigate the effect of the number of simulation scenarios on delay. Then, we compare the end-to-end delays by choosing service times of 0.988 ms and 0.648 ms with 300 ms intervals in Fig. 4 for simulation.

Fig. 7 shows the simulated end-to-end delay from the vehicle to the vehicle via the RSU with a service time of 0.998 ms at the BSMs interval of 300 ms in Fig. 4. Although there is a difference in delay depending on the number of scenarios, they have a similar trend line.

Fig. 8 shows the difference between the numerical results and the NS3 simulation results.

Table 2. Simulation model in NS3

Parameters	Specifications
OS	Ubuntu 20.04.2
Simulator	NS3
Mac Layer Protocol	IEEE 802.11n
Area	300 m × 300 m
Packet size	1024 bytes
Speed of vehicles	10 km/h
Packet transmission frequency	300 ms

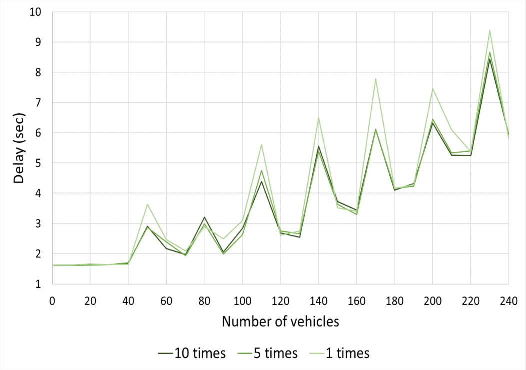

Fig. 7. Comparison of delay according to the number of simulation scenarios in service time 0.998ms

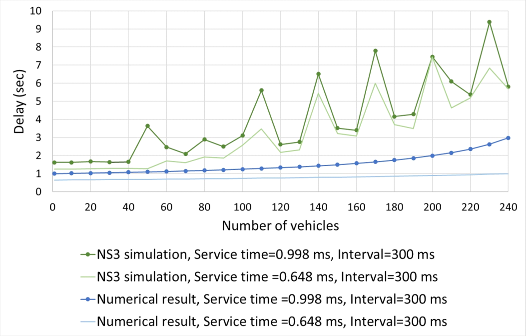

Fig. 8. Simulation with NS3 in service times of 0.998 ms and 0.648 ms

The numerical results represent the outcomes of the two service times selected in Fig. 4. The results of NS3 simulation are an end-to-end delay for vehicle-RSU-vehicle, containing two service times, respectively. In Fig. 8, the difference between numerical results and NS3 simulator results is due to the end-to-end delay of the MAC layer. End-to-end delays include MAC transmission delays[11]. MAC transmission delays are composed of MAC layer random access delay, actual packet transmission delay, and delay caused by channel errors and resulting retransmissions. There is clearly a difference in delay between the two service times of the NS3 simulation. However, this result is more similar to the result that MAC transmission delay increases exponentially with the number of vehicles rather than numerical results. In addition, the cause of the fluctuation in the NS3 simulator result is the lack of simulation scenario, and if more data is accumulated, it will converge to the trend line.

V. Conclusion

In this paper, we have presented the queueing models for RSU relaying and derived the mean system time and mean queue size. In the analysis, the BSMs interval for V2I communication is considered as 100 ms or 300 ms. In BSMs interval is 100 ms, if the number of vehicles is less than 160 and the service time is 0.4166 ms or less (which satisfies $\rho < 1$ in Fig. 2), it can be seen that the difference in system time according to the increase of the vehicles is not significant.

As a result of the overall numerical analysis, the increase in the number of vehicles has a greater effect on the system time than the service time. Therefore, in order to handle the maximum vehicle BSMs according to the traffic volume of the road, the RSU's performance that can support the service time must be accompanied. Alternatively, reducing the maximum number of vehicles handled by the RSU to reliably process BSMs through additional installation of RSU may be one way.

In the further study, we will study the effect of MAC transmission delay with system time and service time on BSMs intervals.

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