Connectivity-based Delay Analysis in MEC-enhanced Vehicular Ad Hoc Networks

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Abstract—**As one of the most critical parts of intelligent transportation systems (ITS), vehicular ad-hoc networks (VANET) has attracted extensive attention both in industry and academia. To cope with the explosive increments of vehicles and the mounting complexity of computing tasks, applying mobile edge computing (MEC) into VANET is an excellent solution. The connectivity probability and the delay are two critical performance metrics for measuring network quality. In this paper, we present the MEC-enhanced VANET architecture to help vehicles executing the computing tasks. The connectivity probability expressions of uplink and downlink in multi-hop of infrastructure based vehicular networks are deduced respectively. Based on the connectivity probability, the MEC offloading computing delay model is proposed. Moreover, the time delay of local computing and MEC offloading computing are compared and analyzed. Numerical results concluded from simulations are presented to give guidance for architecture deployment and resource management.**

Keywords-Connectivity probability; delay; mobile edge computing; vehicular ad hoc networks

I. INTRODUCTION

The explosive increments of vehicles and the mounting complexity of computing tasks make the limited resource more stressful in vehicular ad hoc networks (VANET). To cope with this problem, applying mobile edge computing (MEC) paradigm into the VANET is a good solution. MEC computes the tasks and sends back the results to vehicles to enable the computation-intensive and latency-critical applications at the resource-constrained vehicles [1, 2].

Because the vehicular network is delay-sensitive and resource-limited, it is necessary to propose the edge-based vehicular networks architecture. The MEC offloading framework was proposed [3-5], the authors designed a predictive MEC offloading mechanism [3] and investigated the computation offloading by using delay constraints optimization problem [4, 5]. Integrating several types of wireless communication technologies, a vehicular MEC architecture was proposed [6].

Under the above architectures of vehicular edge computing (VEC), vehicles are fully covered by the infrastructure, i.e. road side units (RSU) or base stations along the road. Vehicles communicate to the infrastructure via vehicle to infrastructure (V2I) communication efficiently. However, the deployment cost of infrastructure is very high. To save the deployment cost of infrastructure, we present the MEC-enhanced VANET architecture where the coverage of RSUs does not overlap with each other. In other words, we expand the allowed distance between two adjacent RSUs. This expanding architecture might cause some vehicles out of the coverage of RSUs directly, while vehicles can connect to RSUs via multi-hop vehicle to vehicle (V2V) communication (vehicle as a relay) [7]. Connectivity of multi-hop V2V relay communication becomes one of the most essential parts of our infrastructure.

The studies on connectivity issues for VANET usually focus on both V2V communication and V2I communication. When analyzing the connectivity probability of V2I communication, researchers usually considered two-hop communications. The authors divided the coverage of vehicles into two categories and analyzed the connectivity probability for one-way V2V and one-way V2I communication [8]. The authors analyzed the access and connectivity probability between a vehicle and the infrastructure in at most two hops [9] and then they extended the 2-hop connectivity probability to derive the uplink and downlink multi-hop connectivity probabilities for infrastructure-based VANET [10].

Due to the delay-sensitive requirement for vehicle's application, the hop count of V2V is restrained. MEC server executes the offloading tasks in order to reduce the delay caused by the multi-hop communication. In MEC offloading studies, the delay is one of the most important issues to focus. Under the constraints of radio access network coverage and computer server network stability, communication latency and computation latency for MEC in wireless networks were analyzed [11]. The delay was described by establishing task queuing models where computation tasks arrive at the mobile devices in a stochastic manner [12]. The end-to-end delay model of the different device was based on the three kinds of offloading model [13].

The above lectures have studied delay model of mobile edge computing offloading problems well. However, they did not discuss the connectivity problem in the expression of delay. In this paper, we present the MEC-enhanced VANET architecture. The coverage of RSUs does not overlap with

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each other in our presented architecture. The uplink and downlink multi-hop connectivity probability expressions of infrastructure-based vehicular networks are given respectively. We combine the connectivity probability with the MEC offloading model and analyze the offloading delay.

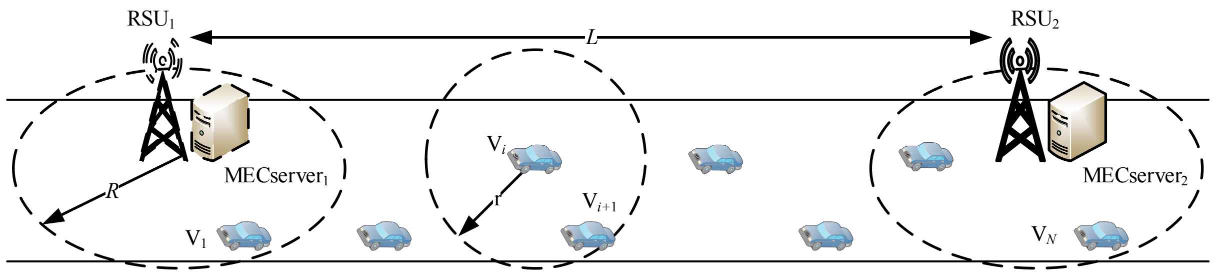


Figure 1. A segment of the MEC-enhanced VANET architecture.

II. SYSTEM MODEL

As shown in Fig. 1, the scenario we consider is a segment of unidirectional and uninterrupted highway, which consists of two adjacent RSUs equipped with MEC servers and N vehicles. Let R and r be the maximum transmission range of RSUs and vehicles respectively. Vehicles and RSUs have the same transmission range, respectively. RSUs communicate with each other through the wired link. Each RSU is equipped with an MEC server. MEC server can help vehicles executing their offloading tasks to reduce the time delay and energy cost. The distance between two adjacent RSUs is L meters. From left to right, the vehicles are V_1, V_2, … , V_N, which V_i denotes the i_{th} vehicle on the line. It is assumed that vehicles are randomly and independently distributed.

The vehicle arrivals are assumed approximated by a Poisson process. The traffic density is defined as λ vehicles per meter. The probability $p(n,L)$ that there are n vehicles in the distance of L meters is

$$p(n,L)=\frac{(\lambda L)^n e^{-\lambda L}}{n!}. \tag{1}$$

Let Δi represent the distance between V_i and V_{i+1} which can be regarded as the interval between two arrivals in a one-dimensional random process. The interval obeys exponential distribution $\lambda e^{-\lambda\Delta i}$ [14]. So, the probability of the distance interval Δi which is no larger than constant distance y is

$$p(\Delta i\le y)=1-e^{-\lambda y}. \tag{2}$$

Two vehicles can communicate with each other as long as their distance is no longer than r. If vehicles are within the transmission range of RSU, they can directly communicate with RSU. Let $h_v(x)$ represent the probability that two vehicles can communicate with each other. Similarly, $h_{rsu}(x)$ is the probability that a vehicle can directly communicate with RSU. Denote x as the distance between two vehicles or the distance between the vehicle and RSU. Then, $h_v(x)$ and $h_{rsu}(x)$ are given by

$$h_v(x)=\begin{cases}1, x\le r\\ 0, else\end{cases}, h_{rsu}(x)=\begin{cases}1, x\le R\\ 0, else\end{cases}. \tag{3}$$

III. CONNECTIVITY PROBABILITY

In this section, we will analyze the multi-hop connectivity probability of VANET. We mainly focus on the connectivity under the circumstance that vehicles are out of the transmission range of RSU. Computing data flow from vehicle to RSU in uplink and the flows turn back in downlink [10]. The downlink and uplink connectivity probabilities will be given respectively.

A. Downlink V2I connectivity probability

We define $p_k^d(x)$, $(k\ge 1)$ as the probability that the vehicle V_i can receive the messages from RSU with the help of k other vehicles as relay nodes. The vehicle V_i is x meters away from the RSU. The superscript d means downlink. The hop count we discuss in this paper is k.

According to [9], the downlink direct connectivity probability, which means that RSU_1 or RSU_2 can directly connect with vehicles, is

$$p_0^d(x)=1-\left(1-h_{rsu}(x)\right)\left(1-h_{rsu}(L-x)\right), \tag{4}$$

where $h_{rsu}(x)$ is given by Eq. (3).

Let $p_1^d(x)$ be the probability that a vehicle located at x is directly connected to at least one vehicle which is directly connected with RSU_1 or RSU_2. It is defined as downlink 1-hop connectivity probability in our paper, which is

$$p_1^d(x)=1-e^{-\int_0^L h_v(\|x-y\|)\lambda p_0^d(y)dy}, \tag{5}$$

where $p_0^d(y)$ is given by Eq. (4) and $\|\cdot\|$ denotes the Euclidean norm.

Eq. (5) is an iterative function, each additional hop is extended on the basis of the previous hop. From the theoretical analysis, we get that $p_k^d(x)$ is related to the expression of $p_{k-1}^d(x)$. The expression of downlink k_{th} hop connectivity probability is

$$p_k^d(x)=1-e^{-\int_0^L h_v(\|x-y\|)\lambda p_{k-1}^d(y)dy}. \tag{6}$$

The integral interval bounds are related to L and x. So, we will discuss $p_k^d(x)$ in three different cases according to the relationship between L and x. The downlink coverage range of k_{th} hop is $x \in \left(R+(k-1)\cdot r, R+k\cdot r\right) \bigcup \left(L-R-k\cdot r, L-R-(k-1)\cdot r\right)$. The specific simplified expressions of three cases are as follows.

Case 1: $2R+(k-1)\cdot 2r < L \le 2R+(k-1)\cdot 2r + r$

$$\begin{gathered} p_k^d(x) = 1-e^{-\int_{x-r}^{R+(k-1)\cdot r} \lambda p_{k-1}^d(y)dy - \int_{L-R-(k-1)\cdot r}^{x+r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(R+(k-1)\cdot r, L-R-(k-1)\cdot r\right) \end{gathered} . \tag{6.1}$$

Case 2: $2R+(k-1)\cdot 2r + r < L \le 2R + k\cdot 2r$

$$p_k^d(x) = \begin{cases} 1-e^{-\int_{x-r}^{R+(k-1)\cdot r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(R+(k-1)\cdot r, L-R-k\cdot r\right) \\ 1-e^{-\int_{x-r}^{R+(k-1)\cdot r} \lambda p_{k-1}^d(y)dy - \int_{L-R-(k-1)\cdot r}^{x+r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(L-R-k\cdot r, R+k\cdot r\right) \\ 1-e^{-\int_{L-R-(k-1)\cdot r}^{x+r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(R+k\cdot r, L-R-(k-1)\cdot r\right) \end{cases} . \tag{6.2}$$

Case 3: $L > 2R + k\cdot 2r$

$$p_k^d(x) = \begin{cases} 1-e^{-\int_{x-r}^{R+(k-1)\cdot r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(R+(k-1)\cdot r, R+k\cdot r\right) \\ 1-e^{-\int_{L-R-(k-1)\cdot r}^{x+r} \lambda p_{k-1}^d(y)dy} \\ x \in \left(L-R-k\cdot r, L-R-(k-1)\cdot r\right) \end{cases} . \tag{6.3}$$

B. Uplink V2I connectivity probability

Similar to the downlink, $p_k^u(x)$ $(k \ge 1)$ is the probability that the RSU (or the vehicle) x meters away from the vehicle v_i can receive the messages from the vehicle v_i through k other vehicles as relay nodes. The superscript u means uplink.

The probability that vehicle can directly connect with RSU_1 or RSU_2, in other words, uplink direct connectivity probability is

$$p_0^u(x) = 1-\left(1-h_v(x)\right)\left(1-h_v(L-x)\right), \tag{7}$$

where $h_v(x)$ is given by Eq. (3).

Let $p_1^u(x)$ be the probability that a vehicle located at x is directly connected to at least one vehicle which is directly connected with RSU_1 or RSU_2, and this probability is

$$p_1^u(x) = 1-e^{-\int_0^L h_v(\|x-y\|)\lambda p_0^u(y)dy}, \tag{8}$$

where $p_0^u(y)$ is given by Eq. (7).

As Eq. (6), the k_{th} hop uplink connectivity probability is

$$p_k^u(x) = 1-e^{-\int_0^L h_v(\|x-y\|)\lambda p_{k-1}^u(y)dy}. \tag{9}$$

The coverage range of uplink k_{th} hop is $x \in \left(k\cdot r, (k+1)\cdot r\right) \bigcup \left(L-(k+1)\cdot r, L-k\cdot r\right)$. The simplified specific expressions are directly given as follows.

Case 1: $2k\cdot r < L \le 2k\cdot r + r$

$$\begin{gathered} p_k^u(x) = 1-e^{-\int_{x-r}^{k\cdot r} \lambda p_{k-1}^u(y)dy - \int_{L-k\cdot r}^{x+r} \lambda p_{k-1}^u(y)dy} \\ x \in \left(k\cdot r, L-k\cdot r\right) \end{gathered} . \tag{9.1}$$

Case 2: $2k\cdot r + r < L \le 2(k+1)\cdot r$

$$p_k^u(x) = \begin{cases} 1-e^{-\int_{x-r}^{k\cdot r} \lambda p_{k-1}^u(y)dy} \\ x \in \left(k\cdot r, L-(k+1)\cdot r\right) \\ 1-e^{-\int_{x-r}^{k\cdot r} \lambda p_{k-1}^u(y)dy - \int_{L-k\cdot r}^{x+r} \lambda p_{k-1}^u(y)dy} \\ x \in \left(L-(k+1)\cdot r, (k+1)\cdot r\right) \\ 1-e^{-\int_{L-k\cdot r}^{x+r} \lambda p_{k-1}^u(y)dy} \\ x \in \left((k+1)\cdot r, L-k\cdot r\right) \end{cases} . \tag{9.2}$$

Case 3: $L > 2(k+1)\cdot r$

$$p_k^u(x) = \begin{cases} 1-e^{-\int_{x-r}^{k\cdot r} \lambda p_{k-1}^u(y)dy} \\ x \in \left(k\cdot r, (k+1)\cdot r\right) \\ 1-e^{-\int_{L-k\cdot r}^{x+r} \lambda p_{k-1}^u(y)dy} \\ x \in \left(L-(k+1)\cdot r, L-k\cdot r\right) \end{cases} . \tag{9.3}$$

IV. CONNECTIVITY-BASED DELAY ANALYSIS

In this section, computing time delay model for tasks is discussed. This model includes the vehicle local computing model and MEC offloading computing model.

Let computing tasks be $\Gamma(d, c, t_{\max})$. Here, d is the data amount of the computing task, c is the number of CPU cycles required to perform the computing task and $t_{\max}$ is the maximum time delay tolerance of the computing task. Regardless of the device on which the task is executed, c is only related to the computing task. When vehicles have computing tasks, they can compute by themselves or choose to offload to MEC servers. In this paper, we consider the binary offloading policy. Binary offloading means computing tasks by computing locally or offloading to MEC server. Local computing and MEC offloading computing will be discussed respectively.

A. Local Computing

Local computing delay t_{loc} is depended on the number of CPU cycles required to perform the computing task and the CPU frequency of vehicles f_0. The local computing delay is

$$t_{loc} = c/f_0 . \tag{10}$$

If $t_{loc} < t_{\max}$, vehicles compute locally. If not, vehicles choose to offload their tasks to MEC server.

B. MEC Offloading Computing

MEC Offloading computing delay $t_{offload}$ includes the uplink delay t_{uplink}, MEC server execution delay t_{exe}^{mec}, and downlink delay $t_{downlink}$, which is

$$t_{offload} = t_{uplink} + t_{exe}^{mec} + t_{downlink} . \tag{11}$$

For wireless channel access, orthogonal frequency-division multiple access (OFDMA) method is adopted. Each V2V link and V2I link is allocated with one sub-channel, respectively. Let B and N denote the bandwidth and the noise power for each sub-channel. p_v denote the transmit power for vehicles. h_{v2v} denote the channel power gain for V2V link. We assume the vehicles have the same transmit power. The V2V transmission rate r_{v2v} is

$$r_{v2v} = B\log_2\left(1+\frac{p_v \cdot h_{v2v}^2}{N}\right). \tag{12}$$

Let b denote the input data amount of the computing task. One hop uplink V2V time delay t_{v2v}^u is

$$t_{v2v}^u = \frac{b}{r_{v2v}} . \tag{13}$$

Let h_{v2i} denote the channel power gain for V2I link. The V2I transmission rate r_{v2i} is

$$r_{v2i} = B\log_2\left(1+\frac{p_v \cdot h_{v2i}^2}{N}\right). \tag{14}$$

Similar to the uplink V2V transmission delay, uplink V2I transmission delay t_{v2i}^u is

$$t_{v2i}^u = \frac{b}{r_{v2i}} . \tag{15}$$

According to the initial position of the vehicle, the hop count k that the vehicle needs to connect to RSU can be calculated. It is assumed that the vehicle offloads its computing tasks to the nearest RSU of its initial position. Uplink delay consists of uplink V2V multi-hop transmission delay and uplink V2I transmission delay, which is

$$t_{uplink} = p_k^u \cdot (t_{v2i}^u + k \cdot t_{v2v}^u) + (1-p_k^u) \cdot t_{out}^{up} , \tag{16}$$

where p_k^u represents uplink k-hop connectivity probability and t_{out}^{up} is the maximum uplink waiting time. If sender cannot get the responses back from receiver within the maximum waiting time, they are not connected and thus the tasks uploading fails.

MEC server execution delay t_{exe}^{mec} is

$$t_{exe}^{mec} = \frac{c}{f} , \tag{17}$$

where f denotes the CPU frequency of MEC. Let b_o be the data amount of the output computing tasks. Downlink V2V transmission delay is

$$t_{v2v}^d = \frac{b_o}{r_{v2v}} . \tag{18}$$

Let p_i denote the transmit power of RSU. Downlink V2I transmission rate r_{i2v} is

$$r_{i2v} = B\log_2\left(1+\frac{p_i \cdot h_{v2i}^2}{N}\right). \tag{19}$$

Downlink V2I transmission delay is

$$t_{v2i}^d = \frac{b_o}{r_{i2v}} . \tag{20}$$

Downlink delay is related to the current position of vehicles. The current position of the vehicle can be computed according to its velocity, its uplink delay, and its MEC server execution time delay. Once the position of the vehicle is determined, the current hop count k' between the nearest RSU and the vehicle can be got. Downlink delay is

$$t_{downlink} = p_{k'}^d \cdot (t_{v2i}^d + k' \cdot t_{v2v}^d) + (1-p_{k'}^d) \cdot t_{out}^{down} , \tag{21}$$

where k' is the hop count from RSU to the vehicle in downlink, t_{out}^{down} is the maximum downlink waiting time, $p_{k'}^d$ is the k'-hop downlink connectivity probability of V2I communication.

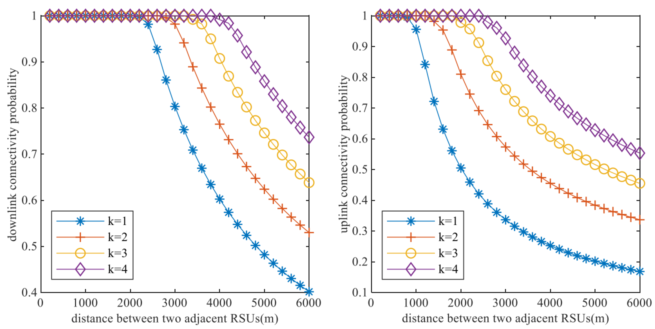
The time delay is the end to end delay. If vehicles offload computing tasks to the MEC server, the time delay includes the uplink delay, MEC execution delay, and downlink delay. Relying on the CPU computing capacity, MEC server mainly reduces the MEC executing delay. Under the actual scene of the vehicular network, with every additional hop, the increasing time delay is more than twice increments. The more count of hop, the larger time delay on the uplink and downlink. However, the local computing delay is regardless of the hop count. In this paper, we analyze the relationship between the distance of two adjacent RSUs and the time delay. The computing tasks we concern are not such critically sensitive to delay. The longer distance means the larger hop count, and then the advantage of MEC offloading computing might not be such obvious. When the hop count achieves the threshold, the offloading delay is likely to exceed the local computing delay. It is our goal to find the maximum hop count to guide the deployment of the RSUs.

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, we verify our theoretical results through simulations. First of all, the multi-hop uplink and downlink connectivity probabilities are analyzed, then the NS3 simulator is used to perform our tests.

The downlink and uplink connectivity probabilities of the vehicular network with different hop count are demonstrated in Fig. 2(a) and Fig. 2(b) respectively. The simulation parameters are $\lambda = 0.01$, $R = 1000\text{m}$ and $r = 300\text{m}$. The 1-4 hop connectivity probabilities can be observed in both uplink and downlink circumstance. To guarantee the delay restraint, the maximum hop count between vehicles is four [7]. It can be found that when k increases by 1, the according turning point moves $2r$ meters to the right. With the same distance, when the hop count increases, the opportunity of connecting to RSU also increases. When k=1, the downlink connectivity probability shows an initial fall at about 2200m, whereas, the uplink connectivity probability shows an initial fall at about 1000m.

Overall, with the increment of L, the connectivity probability decreases regardless of uplink or downlink. When the hop count increases, the connectivity performance is enhanced. The difference between uplink and downlink connectivity probability is the position of the turning point. Uplink connectivity probability is regardless of the transmission radius of RSU. Compared with the downlink, the uplink is harder to maintain a high connectivity probability.



(a) Downlink (b) Uplink

Figure 2. Downlink and uplink k-hop connectivity probability.

We then simulate the VANET scenario in which vehicles offload their computing tasks to the MEC server, and get the computing results back with the average moving speed of 25m/s. The range propagation loss model and the constant speed propagation delay model are used to simulate the wireless channel. Under the 802.11p protocol, OFDM rate27MbpsBW10MHz wireless channel is adopted. The UDP socket is utilized to offload the computing tasks from vehicles to RSU with the help of the AODV routing protocol. The simulation parameters are listed in Table I.

Fig. 3 explains the effect of the transmission radius of vehicles on the time delay. The data size equals 800kbit, the traffic density equals 0.01 here. The transmission radius of vehicles has an effect on the hop count and the hop count mainly affects the uplink and downlink delay. When the radius is 300m and the distance between two adjacent RSUs is 4400m, at this time, the hop count is 4. The offloading computing delay is smaller than local computing delay slightly. It is obvious that local computing is better than offloading computing when the hop count is larger or equal to 5. Based on this, the maximum tolerance hop count is four. Under the constant distance between two adjacent RSUs, the increasing transmission radius leads to the decrement of hop count and the shorter time delay.

TABLE I. LIST OF SIMULATION DATA PARAMETERS

Parameter	Numerical value	Unit
RSU distance	2600~5000	m
Traffic density	0.01~0.03	vehicles/meter
Vehicle speed	25	m/s
Data size	800k~8M	bit
Transmission range	300~500	m
Vehicle CPU	0.7	GHz
MEC CPU	100	GHz

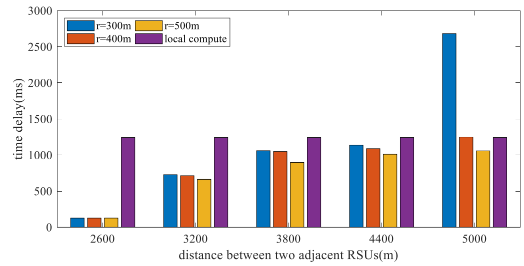


Figure 3. the effect of the transmission radius of vehicles on delay.

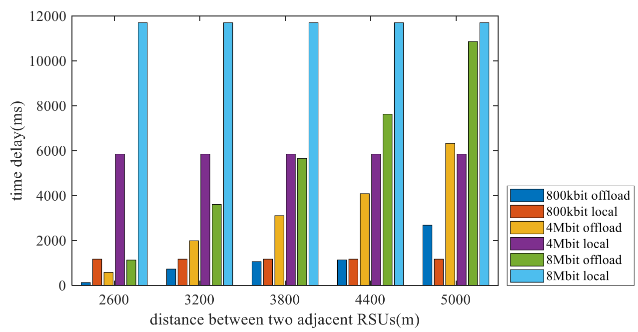


Figure 4. the effect of computing task data size on delay.

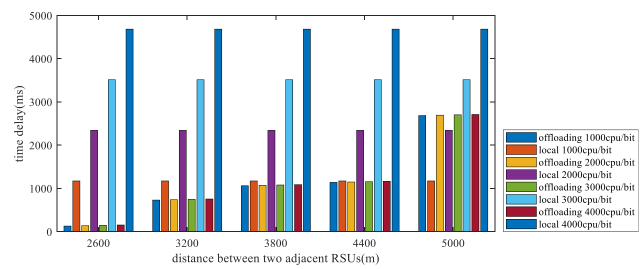


Figure 5. the influence of the computing density on delay.

Fig. 4 explains the effect of computing task data size on the time delay. Here, the transmission radius is 300m and the traffic density is 0.01. With the increase of data size, the advantage of MEC server is more and more obvious. When the data size of the computing task is larger than 8Mbit, the enabled hop count can increase accordingly. With the increments of computing task data size, the needed computing CPU increases accordingly, so does the time delay of local computing. In comparison, the additional delay of MEC offloading delay is less than that of local computing. Under the principle between time delay and hop count, the superiority of MEC offloading computing in saving time delay is likely to be more obvious with large computing task data size.

In order to figure out the influence of the computing density, the computing density is varied from 1000cpu/bit to 4000cpu/bit. Comparison between MEC offloading computing and local computing under different computing density is shown as Fig. 5. Within 4400m, the MEC offloading computing delay is always lower than that of local computing. With the increase of computing density, it is more and more obvious that MEC offloading computing is superior than local computing. So the result figures out that the MEC offloading computing is more suitable for the computing tasks with high computing density.

VI. Conclusions

In this paper, the MEC-enhanced VANET architecture is presented to help vehicles executing the explosively increasing computing tasks. We respectively deduce the uplink and downlink multi-hop connectivity probabilities of infrastructure-based vehicular networks. Then, the connectivity probabilities are applied to our proposed MEC offloading computing delay model. The time delay of local computing and MEC offloading computing are compared and analyzed. It can be concluded that the distance between two adjacent RSUs influences the hop count between the vehicle and the connected RSUs, and thus determines the efficiencies of MEC offloading. Choosing the proper RSUs distance L can save the deployment cost meanwhile guarantee the network performance and avoid unnecessary waste. It is economical and efficient to set the MEC-enhanced VANET architecture in the light of this paper. The specific MEC offloading and RSUs deployment scheme will be given in the future.

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