Design of Analytical Model and Algorithm for Optimal Roadside AP Placement in VANETs

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***Abstract*—The emerging vehicular ad hoc network (VANET) enables vehicles to access the Internet through roadside access points (APs). An important issue in system deployment is determining how many roadside APs shall be installed on a road. However, the existing works fail to provide rigorous and accurate analysis for VANETs. In this paper, we propose a general structure for Internet access in VANETs. It allows both real-time traffic and delay-tolerant traffic to be delivered to users in the most efficient ways. An analytical model is also proposed to analyze the system performance with random arrival of the vehicles. We finally develop an AP placement algorithm based on theoretical results derived from the model to deploy the minimal number of roadside APs with quality-of-service (QoS) guarantees. The simulation results have demonstrated the accuracy of the proposed analytical model and the efficiency of the proposed algorithm.**

***Index Terms*—Analytical model, delay-tolerant traffic, real-time traffic, roadside access point (AP) placement, vehicular ad hoc network (VANET).**

I. Introduction

With the increasing popularity of various types of Internet applications, there is a growing demand for Internet access by services for vehicles, such as car navigation, multimedia streaming, voice/video chatting, and web browsing. The vehicular ad hoc network (VANET) has emerged to enable vehicles to access the Internet via vehicle-to-vehicle (V2V) and vehicle-to-infrastructure communications. Although the cellular-based access techniques (e.g., third generation and long-term evolution) can provide reliable and ubiquitous Internet access to vehicles, it is costly and cannot satisfy the ever-increasing growth of mobile data traffic [1]. Wireless local area network (WLAN) systems (e.g., WiFi) can be deployed with low cost and high performance, and recent research has demonstrated that the WiFi-enabled mobile devices on board can access the Internet when vehicles are moving in the coverage of WiFi hotspots, which is often referred to as drive-thru Internet access [2]. Therefore, the WLAN has become a competitive technology for Internet access in VANETs. To provide reliable Internet access, more roadside access points (APs) are desired. On the other hand, deploying an AP is very costly, and the Internet service provider (ISP) wants to deploy as few APs as possible to save money. Therefore, it is important to determine the minimum number of roadside APs required on a road for a given user quality of service (QoS) requirement.

In WLAN systems, an extensive amount of work was proposed to study the system performance with multihop relays [3], [4] and AP placement [5]. In [5], an AP placement method is proposed to cost-effectively deploy APs with sustainable energy supply and allocate network resources to meet the QoS requirements of users. However, these solutions cannot be used directly in this paper, because the mobility of the vehicles makes the roadside AP deployment problem very different from the WLAN systems. For example, as a vehicle moves on the road, its distance to an AP is constantly changing but predictable. The transmissions can be scheduled at a certain time point with a maximum data rate or at a certain location with minimum interference to the system. Moreover, to the best of the authors' knowledge, there is no analytical model that can accurately model the system performance in VANETs, which considers both real-time traffic data and delay-tolerant traffic data.

In this paper, we develop an analytical model for system performance evaluation in VANETs. Based on the results of the analytical model, we also propose an efficient AP placement protocol for VANETs that enables the ISPs to deploy the minimal number of roadside APs for Internet services with given users' QoS requirements. The original contributions of this paper are listed as follows.

1) We propose a general structure for Internet access in VANETs, which caters for two classes of traffic: real-time traffic and delay-tolerant traffic. This structure utilizes different strategies to deliver these two classes of traffic with optimal system throughput, while preserving fairness among the vehicles.
2) We develop an analytical model for VANETs with Internet access, which estimates the system performance with randomized distances between the vehicles. This is the first work that analyzes the system throughput with combined real-time traffic and delay-tolerant traffic.
3) We present a binary search algorithm to find the maximum length of a road segment that an AP can serve for given users' QoS requirements, and thus, the entire road can be served by using the minimum number of APs.

Manuscript received February 15, 2015; revised July 6, 2015; accepted September 2, 2015. Date of publication October 15, 2015; date of current version September 15, 2016. The review of this paper was coordinated by Dr. C. Chen. *(Corresponding author: Kan Yang.)*

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Digital Object Identifier 10.1109/TVT.2015.2491358

Fig. 1. Segment of the road in VANETs.

The remainder of this paper is organized as follows. We discuss the related work in Section II and present the system model and the problem statement in Section III. A general system structure that caters for both real-time traffic and delay-tolerant traffic is proposed in Section IV. We develop an analytical model of the given traffic delivery strategies in Section V and a planning algorithm for network operators in Section VI. We present the simulation results in Section VII and, finally, conclude this paper in Section VIII.

II. Related Work

The idea of utilizing WiFi technology to provide low-cost Internet services for moving vehicles was introduced by Ott and Kutscher in [2], which is called the drive-thru Internet system. In the proposed system, a limited number of APs are placed on city roads to provide occasional islands of connectivity to the moving vehicles.

There are many existing works that studied the architecture or feasibility [6]–[8] of drive-thru Internet systems. Some of them tried to improve the system performance by utilizing different medium access control or network layer technologies [6]–[17]. However, most of them consider the connectivity of the vehicles to be more important than the system throughput and make all vehicles in the transmission range of an AP share the wireless medium, which degrades the average performance. Some works have been also proposed for wireless coverage issues in WLANs [5] and wireless sensor networks [18]–[24]. In [5], an AP placement method is proposed to cost-effectively deploy APs with sustainable energy supply and allocate network resources to meet the QoS requirements of users. In VANETs, the AP placement problem becomes a challenging issue due to the mobility of vehicles.

The traffic data in VANETs may consist of both real-time data [25]–[27] and delay-tolerant data [28]. In [29], Ota *et al.* proposed a correlation-based approach to predict urban traffic information. They also proposed a cooperative downloading algorithm to minimize an average delivery delay of each user request while maximizing the amount of data packets downloaded from the roadside unit (RSU) [27]. In [30], continuous-time Markov networks are applied to analytically capture the operation of carrier-sense multiple access with collision avoidance (CSMA/CA) networks. Some other works introduced V2V relay schemes [31]–[33] to extend the service range of roadside APs and allow the vehicles to maintain real-time network connections rather than intermittent connections. However, the major problem of V2V relay is the system performance. These schemes do not consider the delay-tolerant traffic and allocate much of the wireless spectrum time frame for long-distance multihop transmissions rather than the more efficient direct transmissions at short distances. Thus, they are not economically efficient for the ISPs.

In this paper, we propose a system structure for two classes of traffic: real-time traffic and delay-tolerant traffic. By separating the network traffic into two classes, there is no connectivity requirement for delay-tolerant traffic. Thus, we are able to take full advantage of the mobility of the vehicles and propose the delivery strategies with optimal theoretical throughput for both classes of traffic. The corresponding analytical model and AP placement algorithm can help the ISPs deploy the minimal number of roadside APs with QoS guarantees.

III. System Model and Problem Statement

In VANETs, APs are deployed along the road, as the RSU, to provide Internet services to the moving vehicles. Since a long road is mostly straight, we assume that the road in our consideration is a straight line and can be divided into segments where one roadside AP (also called a roadside unit) is installed in each segment. Our task is to determine the minimum number of roadside APs required to serve the whole road for the given users' QoS requirements. This objective is equivalent to finding the maximum length of a road segment such that one AP is installed in the middle of the segment and that the QoS requirements can be met. Therefore, we will focus on a subsystem that contains a segment of road, as shown in Fig. 1. In this subsystem, one roadside AP serves all vehicles in this road segment. This road segment is called the *service segment* and denoted by S. The length of the service segment is denoted by d_S, which could be much longer than the transmission range of an AP. The vehicles in a service segment may connect to the AP directly or through some intermediate vehicles. We assume that all antennas installed on the vehicles and the AP are of the same height, because the vehicle antennas are likely to be installed at the similar height, and compared with the horizontal distance of the vehicles, the antenna height difference can be usually negligible. Thus, the distance of any two nodes (i.e., vehicle or AP) can be represented by the difference in their x-coordinate values, and the system can be represented in a 1-D line.

To construct an analytical model, without loss of generality, we make the following assumptions: We assume that the vehicles arrive at Poisson distribution with the arrival rate λ, and all vehicles move toward the same direction with the same speed v, for example, platooning on a highway. The vehicles going the opposite direction will be studied separately in the same way.

We assume that all vehicles and the AP use the maximum allowed transmit power in WiFi systems and, thus, have the same transmission range d_{tx}. For any two nodes v_i and v_j that are within the transmission range, there is a communication link $l_{i,j}$. The transmission data rate $r_{i,j}$ of the link is determined by the distance $d_{i,j}$ of the two nodes.

TABLE I
NOTATIONS

Symbol	Notation
S	service segment
d_S	length of the service segment S of an AP
λ	average vehicles arrive rate
v	stable speed of vehicles on high-way
d_{tx}	transmission range of all vehicles and the AP
v_i, v_j	two nodes within the transmission range
$l_{i,j}$	communication link between v_i and v_j
$r_{i,j}$	transmission data rate of link $l_{i,j}$
$d_{i,j}$	distance between v_i and v_j
d_{inf}	interface range of wireless communications
R_{user_rt}	throughput requirement for real-time traffic
R_{user_dt}	throughput requirement for delay-tolerant traffic
t_{user}	delay bound for delay-tolerant traffic

We use the protocol interference model in this paper. Let d_{inf} denote the interference range of wireless communications. We define the following interference.

- There is interference between a node v_i and a node v_j *iff* $d_{i,j} \leq d_{\text{inf}}$.
- There is interference between a node v_i and a link $l_{j,k}$ *iff* v_i interferes with either v_j or v_k.
- There is interference between a link $l_{i,j}$ and a link $l_{k,l}$ *iff* either v_i or v_j interferes with link $l_{k,l}$.

We consider two classes of network traffic in the system: 1) real-time traffic, which is expected to be delivered in real time, such as the traffic of instant message, online game, and voice or video chat; and 2) delay-tolerant traffic, which allows the messages to be delivered within a tolerable delay (i.e., from a few seconds to 1–2 min), such as the traffic for e-mail, large-file downloading, and multimedia streaming (with sufficient caching). Some of the basic notations are summarized in Table I.

Bandwidth fairness among the vehicles is another objective of the system design. The vehicles that are far away from the AP are often disadvantaged in receiving the end bandwidth. In this paper, we guarantee that all vehicles in the same service segment get a similar amount of traffic. We assume that no vehicle is idle in the system. That is, all vehicles have demand for both real-time and delay-tolerant traffic. This is an extreme case of the system traffic, which can be used to evaluate the system performance in the worst case.

The problem of our consideration is defined as follows. Given the vehicle arrival rate λ and the QoS requirements of the vehicles (including the throughput requirement for real-time traffic $R_{\text{user\_}rt}$ and delay-tolerant traffic $R_{\text{user\_}dt}$ and the delay bound t_{user}), we are going to determine the maximum length d_S of the service segment that an AP can serve. Thus

$$\begin{aligned} \text{Given} \quad & \lambda, R_{\text{user\_}rt}, R_{\text{user\_}dt}, t_{\text{user}} \\ \max \quad & d_S \\ \text{s.t.} \quad & R_{rt} \geq R_{\text{user\_}rt} \\ & R_{dt} \geq R_{\text{user\_}dt} \\ & t_{\text{delay}} \leq t_{\text{user}} \end{aligned}$$

where R_{rt} and R_{dt} are the theoretical per-vehicle throughput for real-time and delay-tolerant traffic, respectively, and t_{delay} is the worst case of delay of delivering a message from a vehicle to a destination.

If d_S is short, it can surely satisfy the QoS requirements, but requires more APs to cover the entire road; if d_S is too long, QoS requirements cannot be met due to too many users to share the bandwidth of the AP and too many hops of transmissions for the vehicles at either end of the segment. There exists an optimal value of d_S. We will present the method to find this optimal d_S in the following sections.

IV. General System Structure for Vehicular Ad Hoc Networks With Internet Access

In this work, we consider two classes of traffic: real-time traffic and delay-tolerant traffic. Since these two classes of traffic have different delivery requirements, we will introduce different delivery strategies to maximize the system throughput.

A. Real-Time Traffic Delivery

In the delivery of real-time traffic, every vehicle needs to maintain real-time network connection to the AP. This real-time connection can be either via a direct link or via some intermediate relays. It is a complicated issue to select the relay nodes for a vehicle, because it depends on the following two factors: 1) the total wireless spectrum time being occupied by transmitting one packet by a direct link or several relay links (this is also referred to as packet transmission time in the following paragraphs) and 2) the interference level of each related link. In the case of a line topology, the traffic is always transmitted along the same straight path. Since every node has the same transmission range, selecting any relay node would have the similar interference to the system. Thus, we will focus on minimizing the packet transmission time. We do not consider the packet-level overhead (e.g., wireless interframe protection spaces and frame headers) in the calculation of packet transmission time, because these overheads heavily depend on the wireless protocol used and the transmission scheduling. Neglecting these overheads enables us to calculate the system raw data rate, which reflects the actual performance well. The existing packet-level analytical models can be applied to this system when we need higher accuracy.

Let p denote the standard data size of a packet. We introduce the *packet transmission time* $t_{i,j}$ over a direct link $l_{i,j}$ as follows:

$$t_{i,j} = \frac{p}{r_{i,j}}. \tag{1}$$

Equation (1) is general for any node pair of v_i and v_j. For the case that v_i has no direct link with v_j, we will have $r_{i,j} = 0$, and $t_{i,j} = \infty$.

Consider a vehicle v_i that is far away from the AP, and there are $i-1$ vehicles between v_i and the AP, namely, $v_{i-1}, v_{i-2}, \ldots, v_2, v_1$ according to their distance to the AP, where v_1 is the closest to the AP. When v_i communicates with an AP, the packet may be relayed through multiple hops. Thus, the packet transmission time between the AP and v_i is the summation of the packet transmission time of all relay links. Let T_i denote the optimal packet transmission time between the AP and v_i and v_0 denote the AP. Note that T_0 is 0. The T_i value for other vehicles can be calculated by the recursive method shown as follows:

$$T_i = \min_{0 \le j < i} \{t_{i,j} + T_j\}. \tag{2}$$

If the minimum T_i is achieved with the help of node v_j, we call v_j the optimal next-hop node of v_i.

The optimal relay path with minimal packet transmission time can be computed by using (2). However, in real systems, the vehicles move at high speed, and their optimal relay path would change from time to time. It is not efficient to let the vehicles recalculate their optimal next hops before every transmission. To solve this problem, we define the *link efficiency* $e_{i,j}$ for link $l_{i,j}$ as the ratio of the packet transmission time to the distance of the link, i.e.,

$$e_{i,j} = \frac{d_{i,j}}{t_{i,j}}. \tag{3}$$

A link with better link efficiency indicates that the link uses shorter transmission time to transmit the packet for a unit distance. Thus, selecting the links with the highest link efficiency in transmissions would help achieve minimal packet transmission time. We can select the next-hop node for a vehicle v_i as follows: 1) Find the node $v_j, 0 \le j < i$ that achieves the highest link efficiency $e_{i,j}$, and 2) let v_j be the next-hop node of v_i. This is called the *max-efficiency relay strategy*. This strategy would achieve a similar result as the recursive method defined by (2) when the distance between the AP and v_i is long.

The next-hop node of any vehicle selected by the max-efficiency relay strategy is stable and does not change for a relatively long period of time. This is because this strategy selects the next-hop node mainly based on the intervehicle link distance and the data rate, which does not change that often, compared with the AP–vehicle distance. Only when a vehicle enters in or exits from the direct transmission range of an AP, or switches between different service segments, shall the next-hop relay node be updated. Thus, the max-efficiency relay strategy can achieve the similar relay throughput with much less computation and operation cost.

B. Delay-Tolerant Traffic Delivery

Many types of Internet traffic are delay tolerant. For example, in most cases, a 1–2-min delay in e-mail delivery is acceptable. For the scenario of large-file downloading, as the transmission process of the file is expected to be relatively long, a short delay in delivery can be tolerated. Even in the case of online media streaming, if a sufficient length of media content is cached, the delivery of the rest of the content is also delay tolerant, because a tolerable delay would not affect the playback of the media.

The delay-tolerant nature of the traffic enables us to make use of the mobility of the vehicles. The transmissions between a vehicle and the AP can be postponed until this vehicle becomes the closest to the AP, where the data rate between this vehicle and the AP is the highest. This is called the *highest data rate delivery* strategy, which makes the AP always transmit or receive data on its highest available data rate. This strategy achieves the theoretical optimal system throughput. However, as the distance between the vehicles is not the same, some vehicles may have a longer period of time during which they are closest to the AP, whereas others have a shorter period of time being closest to the AP. To preserve the throughput fairness among the vehicles, we will present a *carry-and-forward delivery* strategy that balances the bandwidth among the vehicles without affecting the efficiency of the optimal highest data rate delivery strategy. The combined use of these two strategies would achieve the optimal system throughput while preserving fairness among the vehicles.

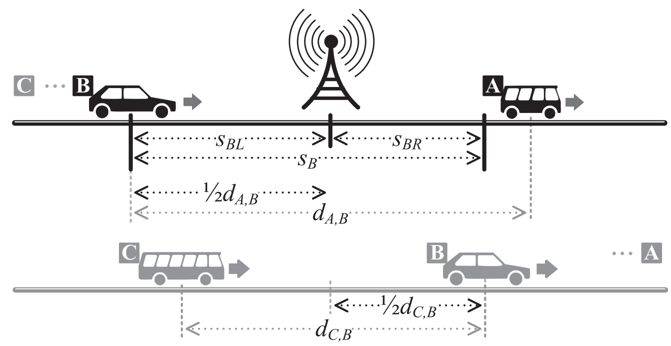

Fig. 2. Loading zone for vehicle B.

1) Highest Data Rate Delivery: The performance of a network system is measured by the total amount of data that are finally delivered to the destinations. As the VANET with Internet access works in infrastructure mode, all traffic in the system is destined to or originated from the AP. When the AP transmits or receives signals, if it is not interfered by the other links, and always selects the link with the highest data rate, the performance of the entire network would be theoretically at maximum.

Consider the transmission policy that the AP always communicates with the closest vehicle in the region. We define the *loading zone* of a vehicle v_i as the part of the road where v_i is the closest vehicle to the AP. As shown in Fig. 2, there is a loading zone s_B for vehicle B. Different vehicles have different loading zones. When a vehicle enters its loading zone, it becomes the closest vehicle to the AP, and the AP only communicates with it. A loading zone can be further divided into two *subzones* by the location of the AP, namely, the left loading zone and the right loading zone. The length of the left loading zone of vehicle v_i is equal to half the distance between v_i and the vehicle ahead of it. For example, the length of s_{BL} is equal to half the distance between vehicles A and B, because when vehicle B enters s_{BL}, it becomes closer to the AP than vehicle A. Similarly, the length of the right loading zone of v_i is equal to half the distance between v_i and the vehicle after it.

For different vehicles, the length of their loading zones can be different. For example, if vehicle B is close to both vehicles A and C, s_B would become very short. Since the amount of data received by a vehicle from the AP is determined by the length of its loading zone, the highest data rate delivery policy is not fair to the vehicles with a short loading zone.

2) Carry-and-Forward Delivery: We introduce a carry-and-forward delivery strategy for downlink traffic of the vehicles, such that the bandwidths of the vehicles could be balanced, whereas the highest theoretical throughput achieved by the highest data rate delivery strategy is not affected.

Initially, the AP estimates the average size of data C_{avg} that can be transmitted in a loading zone. Then, the AP uses the carry-and-forward delivery strategy between the vehicles to ensure that the size of data finally delivered to every vehicle is at least ρC_{avg} (i.e., 90% C_{avg}). The vehicles with a longer loading zone may be selected to carry some downlink traffic for some other vehicles that have a shorter loading zone and forward the traffic to the destination when they move out of the interference range of the AP. The carry-and-forward delivery strategy does not affect the efficiency of the highest data rate delivery strategy, because the transmissions of the forwarding traffic are always scheduled outside the AP's interference range.

In particular, the parameter ρ is configurable. A larger ρ would result in better balanced traffic but with longer intervehicle forwarding time and distance, whereas a smaller ρ would result in less balanced traffic but with shorter intervehicle forwarding time and distance. We will analyze the performance of different values of ρ in the simulation section.

The detailed steps of the carry-and-forward delivery strategy are as follows.

1) The AP transmits downlink traffic to vehicles sequentially using the highest data rate delivery policy.
2) If the length of a loading zone of a vehicle is not sufficient to transmit ρC_{avg} data, the entire loading zone will be used to transmit data for itself, and the rest of the data will be queued at the AP.
3) If the length of a loading zone of a vehicle v_i is long enough to transmit ρC_{avg} data, the ρC_{avg} data of this vehicle will be transmitted first, and the queued data on the AP will be then sent to v_i. If there is no queued data, v_i can make use of this period of time to transmit some extra data for itself.
4) When a vehicle moves out of the interference range of the AP, if it carries some data for the other vehicles, it will forward the data to them.
5) If the requested data are not delivered after a predefined deadline, the data will be redelivered by the AP through the multihop real-time relay connection instead.

V. Analytical Model for Delivery of Real-Time Traffic and Delay-Tolerant Traffic

As we divide the road into segments, the optimal AP placement problem is equivalent to the problem of finding the maximum length d_S of a service segment S. Here, we will present an analytical model to calculate the expected per-vehicle throughput of any given d_S. This analytical model is essential for the planning algorithm of optimal AP placement. Since we utilize different delivery strategies for the two classes of traffic, we will calculate the theoretical per-vehicle throughput R_{rt} for real-time traffic and R_{dt} for delay-tolerant traffic separately.

A. Throughput of Real-Time Traffic

The real-time traffic is connection oriented. Thus, the throughput of real-time traffic mainly depends on the packet transmission time between every vehicle and AP, as well as the interference situation. We will first estimate the packet transmission time.

According to the max-efficiency relay strategy, a vehicle selects a link with the highest link efficiency to transmit the traffic between it and the AP. In practice, since less number of relay hops is usually more efficient in traffic relay, the best length of a relay hop is the transmission range d_{tx}. We define the *relay distance (rd)* of a vehicle to be the distance to its best available vehicle for relay. The relay distance of v_i is determined by the locations of the vehicles between v_i and the AP. As the vehicles arrive in a random process, the relay distance is also a random variable between 0 and d_{tx}. Let $f_{rd}^{\text{pdf}}(d)$ denote the probability density function (pdf) of the relay distance. It can be used to calculate the probability density of any given relay distance d. $f_{rd}^{\text{pdf}}(d)$ can be formulated as

$$f_{rd}^{\text{pdf}}(d) = \lambda \times e^{-\lambda(d_{tx}-d)}, \quad 0 \le d \le d_{tx}. \tag{4}$$

The average packet transmission time of a direct link with distance d is

$$t(d) = \frac{p}{r(d)}, \quad 0 \le d \le d_{tx}. \tag{5}$$

$r(d)$ is the data rate of a link where the distance of two end nodes is equal to d.

In multihop relay systems, the traffic may be relayed in multiple links. Let $T(d)$ denote the average packet transmission time between vehicle v_i and the AP with distance d using a multihop relay. Suppose v_k is the relay node for v_i, the packet transmission time between v_i and the AP is equal to the packet transmission time between v_i and v_k, plus the packet transmission time between v_k and the AP. This could be a recursive calculation, because v_k may be also far away from the AP and has to use some relays for communication. As the relay distance between v_i and v_k is a random variable, we can calculate $T(d)$ using the following recursive method:

$$T(d) = \begin{cases} \int_0^{d_{tx}} \left(T(d-x)+t(x)\right) f_{rd}^{\text{pdf}}(x)dx, & \text{if } d > d_{tx} \\ t(d), & \text{if } 0 \le d \le d_{tx}. \end{cases} \tag{6}$$

In multihop relay systems, any two interfering links cannot transmit simultaneously. Suppose we have the amount of traffic scheduled to be transmitted on each link and a timeframe T for transmitting all traffic on the link. Let $L_I(v_k)$ denote the set of links that interfere with node v_k. The *interference constraint* is defined as follows.

For any link set $L_I(v_k)$, the summation of the transmission time required for transmitting the traffic on these links shall never exceed T.

To deliver real-time traffic, every vehicle in the system maintains a real-time connection to the AP either via a direct communication link or via some intermediate relays. These multihop communication routes form a tree, where the AP is the root. The throughput of such a multihop system highly depends on the interference of the links. It is obvious that the bottleneck of the network is at the AP, because all traffic is originated from or destined to the AP. Therefore, when calculating the packet transmission time between any two nodes, we can consider only the total transmission time required by the links in set $L_I(\mathrm{AP})$. By doing so, the interference constraint can be easily verified. Let $T_{\mathrm{AP}}(d)$ denote the transmission time required by $L_I(\mathrm{AP})$ of transmitting a packet between a vehicle and the AP with distance d. $T_{\mathrm{AP}}(d)$ can be expressed as

$$T_{\mathrm{AP}}(d) = \begin{cases} \int_0^{d_{tx}} T_{\mathrm{AP}}(d-x) f_{rd}^{\mathrm{pdf}}(x)dx, & \text{if } d \geq d_{\inf} + d_{tx} \\ \int_0^{d-d_{\inf}} T_{\mathrm{AP}}(d-x) f_{rd}^{\mathrm{pdf}}(x)dx & \\ + \int_{d-d_{\inf}}^{d_{tx}} (T(d-x)+t(x)) f_{rd}^{\mathrm{pdf}}(x)dx, & \text{if } d_{\inf} < d < d_{\inf} + d_{tx} \\ T(d), & \text{if } 0 \leq d < d_{\inf}. \end{cases} \tag{7}$$

For a vehicle inside the service segment of an AP, its distance to the AP is constantly changing. The average transmission time required by $L_I(\mathrm{AP})$ of transmitting a packet between this vehicle and the AP is

$$T_{\mathrm{avg}} = \frac{\int_0^{\frac{d_S}{2}} T_{\mathrm{AP}}(x)dx}{\frac{d_S}{2}} = \frac{2\int_0^{\frac{d_S}{2}} T_{\mathrm{AP}}(x)dx}{d_S}. \tag{8}$$

According to the Poisson distribution, the average number of vehicles in a service segment is λd_S. That is, the expected transmission time used for every vehicle to transmit a packet with the AP is $T_{\mathrm{avg}}\lambda d_S$. Thus, the per-vehicle throughput of real-time traffic is

$$R_{rt} = \frac{p}{T_{\mathrm{avg}}\lambda d_S} = \frac{p}{2\lambda \int_0^{\frac{d_S}{2}} T_{\mathrm{AP}}(x)dx}. \tag{9}$$

B. Throughput of Delay-Tolerant Traffic

The delay-tolerant traffic is delivered intermittently. It is transmitted from the AP to a vehicle only when this vehicle is inside its loading zone. To calculate the expected per-vehicle throughput R_{dt} for delay-tolerant traffic, we will first calculate the average size of data transmitted in a loading zone. Since a vehicle is only served once by an AP in a service segment and the total time a moving vehicle stays in this service segment is known, we will be able to calculate the per-vehicle throughput.

1) Length of a Subzone: Since we assume that the arrival of the vehicles follows Poisson distribution with the arrival rate λ, the distance between any two consecutive vehicles follows the exponential distribution with parameter λ. Let $f_{\mathrm{vvd}}^{\mathrm{cdf}}(d)$ denote the cumulative distribution function (cdf) of the vehicle-to-vehicle distance (vvd) between any two consecutive vehicles. This function can be defined as follows:

$$f_{\mathrm{vvd}}^{\mathrm{cdf}}(d) = 1 - e^{-\lambda d}. \tag{10}$$

Since the length of a subzone (i.e., a left loading zone or a right loading zone) is equal to half of the vvd, it is also a random variable. Let $f_{\mathrm{szd}}^{\mathrm{cdf}}(d)$ denote the cdf of a subzone's distance (szd). It can be formulated as follows:

$$f_{\mathrm{szd}}^{\mathrm{cdf}}(d) = f_{\mathrm{vvd}}^{\mathrm{cdf}}(2d) = 1 - e^{-\lambda 2d}. \tag{11}$$

2) Size of Data Transmitted in a Loading Zone: When a vehicle moves inside any subzone with distance d, its distance to the AP changes either from 0 to d or from d to 0. Let $C(d)$ denote the total size of traffic that can be transmitted in a subzone with distance d. Since we assume that the vehicle moves at an even speed v, $C(d)$ can be calculated as follows:

$$\begin{aligned} C(d) &= \int_0^d r(x)dt \\ &= \int_0^d r(x)d\frac{x}{v} \\ &= \frac{1}{v}\int_0^d r(x)dx. \end{aligned} \tag{12}$$

Equation (12) can be used to calculate the size of data that can be transmitted within a subzone with distance d. Given a size of data c, we can use the reverse function of (12) to calculate the length of the subzone required, i.e.,

$$d = C^{-1}(c). \tag{13}$$

As the length of a subzone is a random variable, the size of data that can be transmitted in a subzone is also a random variable. Let z denote a random loading zone and $(1/2)z$ a subzone (i.e., half of a loading zone). Let $f_{(1/2)z}^{\mathrm{cdf}}(c)$ denote the cdf of the size of data c that can be transmitted in a subzone. It can be expressed by substituting (13) into (11) as follows:

$$\begin{aligned} f_{\frac{1}{2}z}^{\mathrm{cdf}}(c) &= f_{\mathrm{szd}}^{\mathrm{cdf}}\left(C^{-1}(c)\right) \\ &= 1 - \lambda e^{-\lambda 2C^{-1}(c)}. \end{aligned} \tag{14}$$

We could derive the corresponding pdf as follows:

$$f_{\frac{1}{2}z}^{\mathrm{pdf}}(c) = \frac{d\left(f_{\frac{1}{2}z}^{\mathrm{cdf}}(c)\right)}{dc}. \tag{15}$$

Let $f_z^{\mathrm{pdf}}(c)$ denote the pdf of the size of data c that can be transmitted in a full loading zone. It represents the probability density of any given size of data c to be transmitted within a full loading zone. Since a loading zone contains two individual subzones, it can be formulated as the self-convolution of $f_{(1/2)z}^{\mathrm{pdf}}(c)$, i.e.,

$$f_z^{\mathrm{pdf}}(c) = \left(f_{\frac{1}{2}z}^{\mathrm{pdf}} * f_{\frac{1}{2}z}^{\mathrm{pdf}}\right)(c). \tag{16}$$

Let C_{avg} denote the average size of data that can be transmitted in a random loading zone. C_{avg} can be then calculated as follows:

$$C_{\mathrm{avg}} = \int_0^{\infty} f_z^{\mathrm{pdf}}(x) x dx. \quad (17)$$

3) Average Per-Vehicle Throughput: Consider the case that all vehicles move at an even speed v in the system, and there is a service segment of an AP with distance d_S. For any moving vehicle, the time of this vehicle to stay in this service segment is d_S/v. Since this vehicle is only served once by the AP during this period of time and the average size of data received is C_{avg}, we are able to calculate the average per-vehicle throughput of delay-tolerant traffic as follows:

$$R_{dt} = \frac{C_{\mathrm{avg}}}{\frac{d_S}{v}} = C_{\mathrm{avg}} \frac{v}{d_S}. \quad (18)$$

C. Total Throughput

We now have the theoretical per-vehicle throughput for both real-time and delay-tolerant traffic delivery strategies. We will jointly use these two strategies to increase the flexibility of the system. Let α denote the ratio of system transmission time allocated for real-time traffic and β for delay-tolerant traffic. We can update calculations of R_{rt} and R_{dt} as follows:

$$\begin{aligned} R_{rt} &= \alpha \frac{p}{2\lambda \int_0^{\frac{d_S}{2}} T_{\mathrm{AP}}(x) dx} \\ R_{dt} &= \beta C_{\mathrm{avg}} \frac{v}{d_S}. \end{aligned} \quad (19)$$

They can be used to verify whether the theoretical per-vehicle throughput for both classes of traffic satisfies the users' QoS requirements R_{user_rt} and R_{user_dt}.

We can calculate the total per-vehicle throughput R_{total} as follows:

$$\begin{aligned} R_{\mathrm{total}} &= R_{rt} + R_{dt} \\ &= \alpha \frac{p}{\lambda \int_0^{d_S} T_{\mathrm{AP}}(x) dx} + \beta C_{\mathrm{avg}} \frac{v}{d_S}. \end{aligned} \quad (20)$$

Note that the total transmission time allocated $\Gamma = \alpha + \beta$ can be less than 100%, because we only consider the vehicles moving toward the same direction. The vehicles in the opposite direction are considered as under a different system, and they share the same wireless spectrum.

D. Delay Bound Analysis of Delay-Tolerant Traffic

Apart from the throughput, the delay bound of traffic delivery would also affect the service quality of the system. There are two types of delay in delivering a message to a destination vehicle. The first type of delay is caused by the highest data rate delivery strategy, which is denoted by t_{delay_hd}, because this strategy always selects the vehicle with the highest data rate to receive data from an AP and postpones the transmissions of the other vehicles. The second type of delay is caused by the carry-and-forward strategy, which is denoted by t_{delay_cf}, because this strategy enables the vehicles to postpone the intervehicle relay traffic until they get out of the interference range of an AP. The worst case delay in delivering a message to a destination vehicle is the summation of the two types of delay, i.e.,

$$t_{\mathrm{delay}} = t_{\mathrm{delay}\_hd} + t_{\mathrm{delay}\_cf}. \quad (21)$$

As the users' QoS requirement for delivery delay is defined to be t_{user}, we must ensure that the worst-case delay t_{delay} is smaller than t_{user}.

For the highest data rate delivery strategy, given the distance d_S of a service segment and the moving speed v of the vehicles, we can calculate t_{delay_hd} as follows, which represents the worst case interval that a vehicle cannot access any AP:

$$t_{\mathrm{delay}\_hd} = \frac{d_S}{v}. \quad (22)$$

Suppose the vehicles are numbered as $v_1, v_2, \ldots, v_n$ from the right side to the left side of the road. According to the process of delay-tolerant traffic delivery introduced in Section IV, once a vehicle v_k cannot receive the desired amount of data ρC_{avg}, the vehicle after it (i.e., v_{k+1}) would offer help. If these two vehicles cannot receive the desired amount of data $2\rho C_{\mathrm{avg}}$, the vehicle after them (i.e., v_{k+2}) would offer help. This process continues until a vehicle v_{k+x} arrives, and the total amount of data received by the vehicles $v_k, v_{k+1}, \ldots, v_{k+x}$ is greater than $(x+1)\rho C_{\mathrm{avg}}$. We define a *cooperative group* to be a sequence of consecutive vehicles, such that the total amount of data transmitted from the AP to these vehicles is larger than the total size of data that shall be guaranteed for them. We define the size of a cooperative group to be the number of vehicles in it.

For the carry-and-forward delivery strategy, there are three types of delay as follows.

1) In case that a vehicle does not receive sufficient data in its loading zone, the transmission is postponed, and the traffic will be delivered to another vehicle in the cooperative group. Let N_{avg} denote the average size of a cooperative group, the worst case of this delay can be expressed as $N_{\mathrm{avg}}/\lambda v$.
2) The intervehicle traffic is carried by some vehicles until they move out of the interference range of the AP. This delay can be expressed as d_{inf}/v.
3) It takes some time for a vehicle to forward the traffic to a destination vehicle. Let C_{relay} denote the average size of relayed data transmitted in a cooperative group, this delay can be expressed as $(C_{\mathrm{relay}}/p) \times T((N_{\mathrm{avg}}) - 1/\lambda)$, where $(N_{\mathrm{avg}} - 1)/\lambda$ is the worst-case distance of intervehicle traffic relay in a cooperative group.

The average delivery delay of the carry-and-forward delivery strategy can be then calculated as follows:

$$t_{\mathrm{delay}\_cf} = \frac{N_{\mathrm{avg}}}{\lambda v} + \frac{d_{\mathrm{inf}}}{v} + \frac{C_{\mathrm{relay}}}{p} \times T\left(\frac{N_{\mathrm{avg}} - 1}{\lambda}\right). \quad (23)$$

We will calculate N_{avg} and C_{relay} in the following paragraphs. Suppose a vehicle is the first vehicle of a cooperative group (i.e., the rightmost vehicle), and it does not receive sufficient data within its loading zone (i.e., there must be at least two vehicles in this cooperative group). Let $f_{z-}^{\text{pdf}}(c)$ denote the pdf of the size of traffic this vehicle receives. It can be expressed as follows:

$$f_{z-}^{\text{pdf}}(c) = \begin{cases} f_z^{\text{pdf}}(c), & \text{if } 0 \leq c \leq \rho C_{\text{avg}} \\ 0, & \text{if } c < 0 \text{ or } c > \rho C_{\text{avg}}. \end{cases} \tag{24}$$

For the kth vehicle in a cooperative group, if it does not receive sufficient traffic within its loading zone (i.e., there are at least $k+1$ vehicles in this cooperative group), the pdf of the size of traffic that all these k vehicles receive is

$$f_{kz-}^{\text{pdf}}(c) = \begin{cases} \left(f_{(k-1)z-}^{\text{pdf}} * f_z^{\text{pdf}}\right)(c), & \text{if } 0 \leq c \leq k\rho C_{\text{avg}} \\ 0, & \text{if } c < 0 \text{ or } c > k\rho C_{\text{avg}}. \end{cases} \tag{25}$$

The probability that the size of a cooperative group N is greater than k (i.e., at least $k+1$) is

$$P(N > k) = \int_0^\infty f_{kz-}^{\text{pdf}}(x)dx, k \geq 1. \tag{26}$$

In particular, $P(N > 0) = 1$. The probability that the size of a cooperative group N is equal to k is

$$P(N = k) = P(N > k) - P(N > k-1), k \geq 1. \tag{27}$$

The average size of a cooperative group N_{avg} for traffic relay can be then calculated as follows:

$$N_{\text{avg}} = \sum_0^\infty P(N = k) \times k. \tag{28}$$

In a cooperative group, the total size of relayed data transmitted by the vehicles is equal to the total size of relayed data received by them. Thus, to calculate C_{relay} for a vehicle, we can just calculate the total size of data that is required by the vehicles with insufficient length of loading zones, i.e.,

$$C_{\text{relay}} = N_{\text{avg}} \int_0^{\rho C_{\text{avg}}} f_z^{\text{pdf}}(x)(\rho * C_{\text{avg}} - x)dx. \tag{29}$$

VI. Planning Algorithm for Optimal Access Point Placement

The objective of the optimal AP placement problem is equivalent to finding the maximum length of a service segment with one AP that the users' QoS requirements can be met. Thus, the planning algorithm presented in this section will focus on the maximum length of a service segment. The problem is defined as follows. The network settings (i.e., speed v, arrival rate λ, and allocatable transmission time ratio Γ) and the QoS requirements R_{user_rt} and R_{user_dt} are given. We are going to determine the maximum distance d_S of the service segment, as well as the optimal ratio α and β used for either real-time traffic or delay tolerant traffic, such that the QoS requirements can be satisfied.

Since we are able to calculate the per-vehicle throughput for any given d_S, we can use a binary search method to calculate the optimal d_S.

A. Bounds of d_S

For the given β and R_{user_dt}, we can use (19) to calculate the maximum d_S that an AP can support. Suppose we allocate all transmission time to delay-tolerant traffic, i.e., $\beta = \Gamma$, and only consider the QoS requirement of delay-tolerant traffic. The calculated maximum d_S can be regarded as the upper-bound distance, because by adding the consideration of the QoS requirement of real-time traffic, an AP can no longer serve so large an area with QoS guarantees, and the length of the service segment would definitely reduce. Let d_{S+} denote the upper-bound distance of d_S, it can be calculated as follows:

$$d_{S+} = \Gamma C_{\text{avg}} \frac{v}{R_{\text{user}\_dt}}. \tag{30}$$

The lower bound d_{S-} can be assumed to be 0 in the initial state.

B. Binary Search of d_S

After we find the upper and lower bounds of d_S, we can use the binary search method to find the optimal length d_S, as shown in Algorithm 1. We can then optimally place the APs on the road with distance d_S.

Algorithm 1 BiSearch d_S

Input d_{S+} ▷ the upper-bound distance of d_S
Input d_{S-} ▷ the lower-bound distance of d_S
Output d_S ▷ the optimal length of d_S
while R_{rt} is not close enough to R_{user_rt} **do**
  $d_{S\_mean} \leftarrow (d_{S+} + d_{S-})/2$; ▷ the current segment length
  Calculate the minimum β required to make $R_{dt} \geq R_{\text{user}\_dt}$;
  Calculate transmission time ratio $\alpha = \Gamma - \beta$;
  Calculate the expected throughput for real-time traffic R_{rt} with α;
  if $R_{rt} > R_{\text{user}\_rt}$ **then**
    $d_{S-} = d_{S\_mean}$; ▷ as the AP has the potential to provide service to a larger area
  end if
  if $R_{rt} < R_{\text{user}\_rt}$ **then**
    $d_{S+} = d_{S\_mean}$; ▷ as the AP cannot support this length of service segment
  end if
end while
return $d_S = d_{S\_mean}$;

VII. Simulation Results

In the simulation, we created a one-way highway model of 10 000 m in SUMO 0.23, where the highway has four lanes

TABLE II
PARAMETERS USED IN SIMULATION

Notation	Description	Default value
d_{tx}	transmission range	300 m
d_{inf}	interference range	600 m
P_N	background noise power	-90 dBm
A_{base}	signal attenuation at 1 meter	-40 dB
a	path loss exponent	2.5
B	wireless bandwidth	20 MHz

and three entrances. We simulate the traffic on the highway for half an hour. In the simulated traffic data set, the vehicles enter the highway randomly from different entrances. The arrival rate and the speed of the vehicles change from time to time. The average vvd is 44.29 m, and average speed is 24.78 m/s (i.e., 89.2 km/h). To evaluate the accuracy of the analytical model, we developed a simulator by C#. The wireless transmission parameters used in the simulation are listed in Table II. The data rate between any two nodes with distance d is assumed to follow the Shannon–Hartley theorem and can be calculated as follows:

$$r(d) = 0.332B(P_{rx}(d) - P_N) \tag{31}$$

where $P_{rx}(d)$ denotes the received signal strength (in dBm) at distance d and can be calculated as follows:

$$P_{rx}(d) = P_{tx} + A_{\text{base}} - a \times 10 \times \log_{10}(d). \tag{32}$$

The vehicles in the highway use the delivery strategies presented in Section IV for both real-time traffic and delay-tolerant traffic. As we do not consider the packet-level traffic scheduling in this work, the simulator evaluates the system performance by packet transmission time between the nodes and does not simulate/schedule the transmissions at the packet level. That is, the system performance is measured in RAW data rate (the theatrical data rate without considering the packet-level overhead).

A. Average Throughput

We first simulate the cases of the vehicle system with different service segment distance d_S values. We allocate 50% of the transmission time for real-time traffic and another 50% of the transmission time for delay-tolerant traffic. As shown in Fig. 3, the analytical results are very close to the simulation results, particularly for the real-time traffic (with only 0.11% difference). The simulation result is 4.79% better than the analytical result on delay-tolerant traffic. This is because the vvd in the same lane tends to be smoothed out in a long run (i.e., the vehicles will not become too close or too far away). Note that the scaling of the y-axis is in logarithm. As d_S grows, the throughput of delay-tolerant traffic could be more than ten times higher than real-time traffic. This is because the delay-tolerant traffic of a vehicle is always delivered through a direct link at the highest data rate, whereas the real-time traffic of a vehicle can be relayed for many hops.

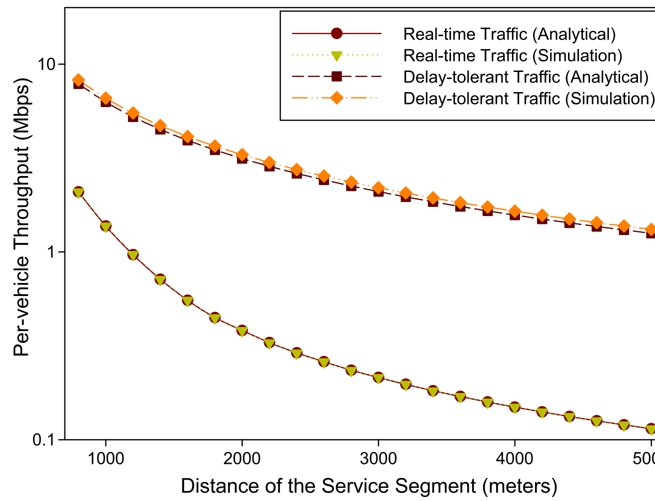

Fig. 3. Comparison of average per-vehicle throughput.

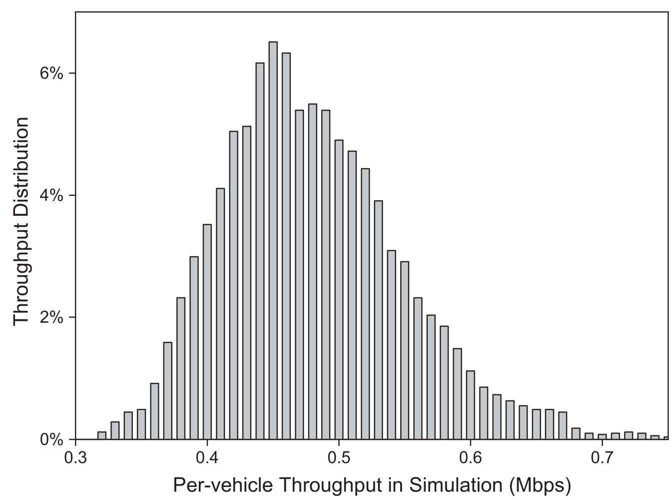

Fig. 4. Distribution of per-vehicle throughput for real-time traffic.

B. Throughput Distribution

As the vehicles arrive in a random process, the number of vehicles in a service segment can be different from time to time. Fig. 4 shows the distribution of per-vehicle throughput for real-time traffic when $d_S = 3000$ m and when $\alpha = 100\%$. There is no throughput balance algorithm used in real-time traffic delivery. That is, when the density of the vehicles in a service segment becomes higher, the throughput of all vehicles in this service segment would decrease. However, for most cases, the vehicles can still achieve reasonable throughput. For example, for more than 90% of the cases, the vehicles could achieve at least 80% of the expected throughput.

In a delay-tolerant traffic delivery system, the situation becomes different, because we utilize the carry-and-forward strategy to balance the traffic between vehicles to preserve throughput fairness. Fig. 5 shows the distribution of per-vehicle throughput for delay-tolerant traffic when $d_S = 3000$ m, $\beta = 100\%$, and $\rho = 90\%$. That is, we balance the traffic among the vehicles to make every vehicle achieve at least 90% of the expected throughput. As shown in the figure, more than 67% of the vehicles achieve the throughput around the lower bound, while some vehicles achieve higher throughput.

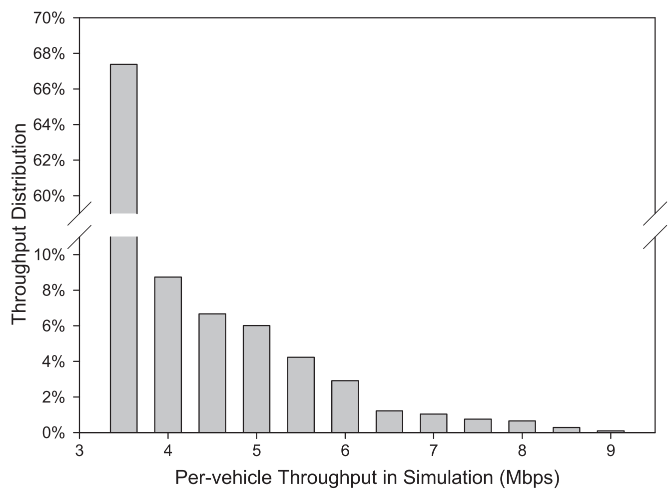

Fig. 5. Distribution of per-vehicle throughput for delay-tolerant traffic.

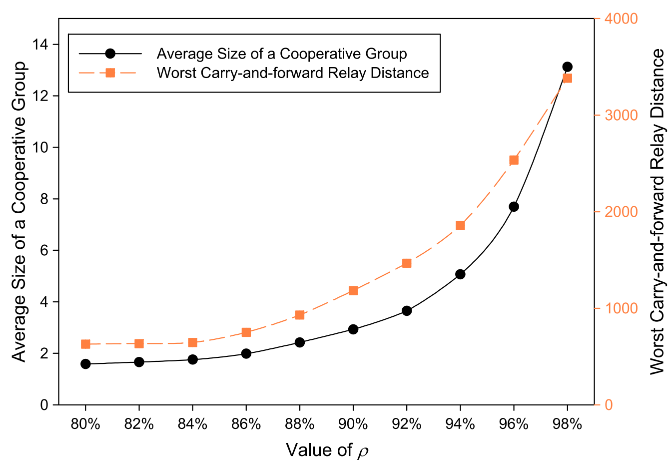

Fig. 6. Average size of the cooperative group with different ρ values.

C. Selection of ρ

In the delivery of delay-tolerant traffic, the carry-and-forward strategy is used to relay the traffic between the vehicles to ensure that every vehicle would have at least a ratio ρ of average per-vehicle throughput. This ratio ρ represents the extent of the desired balance of traffic among the vehicles. A larger ρ would result in better balanced traffic but with a longer intervehicle relay distance, whereas a smaller ρ would result in less balanced traffic but with a shorter intervehicle distance.

Fig. 6 shows the average size N_{avg} of cooperative groups and the worst case carry-and-forward relay distance with different ρ values. As ρ grows, there would be more vehicles to receive an insufficient amount of data and more traffic to be relayed. Thus, a vehicle would take longer hops to find another vehicle to relay data, which results in larger size of cooperative groups. As shown in the figure, when ρ is selected to be higher than 95%, the average relay distance dramatically increases, and the traffic may need to be relayed outside the service segment. Selecting ρ around 90% would be a good choice, because it helps preserve reasonable fairness of the vehicles, whereas the size of the cooperative group does not significantly increase.

VIII. Conclusion

In this paper, we have developed a general system structure to maximize the system performance of vehicle networks. For real-time traffic, the links with maximum link efficiency were used to a construct multihop relay tree rooted from the AP to deliver the traffic. For delay-tolerant traffic, the highest data rate delivery and the carry-and-forward strategy were utilized to deliver the traffic with the optimal throughput while preserving fairness among the vehicles. An analytical model was proposed to evaluate the system performance, and a binary search algorithm was presented to enable the operators to deploy a minimal number of roadside APs while satisfying the QoS requirements of the vehicles.

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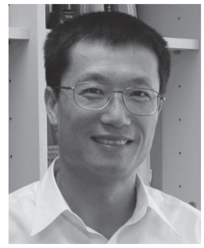

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