Opportunistic Vehicle-to-Vehicle Relay with Adaptive Modulation for Drive-Thru Internet Access

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***Abstract*—Drive-thru Internet is a promising technique that exploits the inter-connected roadside access points (APs) to offer Internet access. However, there will be very high costs to deploy and maintain a large number of APs to provide ubiquitous coverage. There are many studies on vehicle-to-vehicle (V2V) relay to further improve the performance of the drive-thru Internet system. In this paper, we investigate an opportunistic V2V relay protocol with adaptive modulation and propose an analytical approach to evaluate the access performance in terms of average packet delay and overall success probability. Based on the analysis, the modulation modes can be adapted to guarantee a required transmission success probability while minimizing the average packet delay. The numerical and simulation results demonstrate the accuracy of the analysis and the effectiveness of the proposed V2V relay protocol with adaptive modulation.**

***Index Terms*—Drive-thru Internet, vehicular networks, V2V relay, opportunistic relay, adaptive modulation.**

I. Introduction and Related Work

Drive-thru Internet [1] is a promising technique that exploits inter-connected access points (APs) placed along roads to enable Internet access for vehicular users on the move. Different from the cellular networks such as the Long Term Evolution (LTE) [2] that have ubiquitous coverage, the roadside APs usually only provide intermittent connectivity. The uplink and downlink performance of the drive-thru Internet has been analyzed in [3,4]. It is found that the coverage of APs and vehicle density and speed have substantial impact on the achievable performance. In the literature, there have been many studies on engaging vehicle-to-vehicle (V2V) relay to further complement the limited coverage of roadside APs [5]–[8]. Relay selection becomes an essential problem considering the high mobility of vehicles.

In [5], a multi-hop V2V relay protocol is proposed for adaptive video streaming service. In the proposed relay protocol, a source vehicle takes advantage of broadcast beacon messages of neighbors to obtain their locations, speeds, directions, and estimated data rates to the roadside APs. The relay selection is source-centered and the source basically selects the neighbor vehicle with the highest data rate to a roadside AP. An opportunistic relay protocol is proposed in [6] for the drive-thru Internet. In the opportunistic relay protocol, the AP first broadcasts the data and all vehicles that successfully receive the data contend to relay it to the destination. Each relay vehicle sets its contention window according to its distance to the destination. A priority (smaller contention window) is given to the vehicle with a higher expected data rate, i.e., generally closer to the destination. The study in [6] considers the trade-off between the broadcast data rate and the achievable throughput. A lower broadcast rate with a large transmission range increases the number of relay candidates and the chance of having good relays. Nonetheless, the priority scheme is assumed to work perfectly. Actually, more candidates also lead to more intense contention in the forwarding. Hence, the analysis in [6] may not be able to determine the best broadcast rate, especially for a scenario of a high vehicle density.

Due to the high mobility of a vehicular environment, a centralized solution of V2V relay selection can be subject to obsolete information with the fast-changing topology. Hence, we consider an opportunistic V2V relay protocol so as to improve the access performance of the direct transmission from a roadside AP (source) to a destination vehicle. Each potential relay vehicle that successfully overhears a packet from the AP independently determines a random backoff time depending on its estimated transmission success probability to the destination. A relay vehicle of a good channel condition to the destination should end up with a short backoff time, so that it is prioritized when forwarding the packet to the destination. Moreover, we take into account adaptive modulation at the roadside AP and the relay vehicles. An analytical approach is proposed to address the trade-off of including sufficient relay candidates and mitigating contention among them. Based on the proposed analysis, we are able to figure out the best modulation rates for the source AP and the winner relay vehicle. The numerical results well demonstrate that the opportunistic relay protocol with the selected modulations can satisfy the required transmission success probability while minimizing the transmission delay. The accuracy of the proposed analysis is also verified by simulations.

The rest of the paper is organized as follows. In Section II, we present the system model and problem formulation. In Section III, we introduce our analysis of an opportunistic V2V relay protocol with adaptive modulation. Numerical results are given in Section IV, followed by conclusions in Section V.

II. System Model and Problem Formulation

A. System Model

In this paper, we consider the drive-thru Internet access system illustrated in Fig. 1, in which the vehicular users

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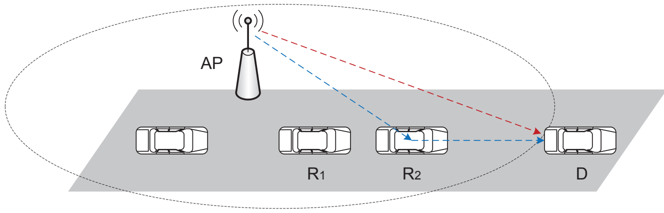


Fig. 1. System model of drive-thru Internet access with V2V relay.

can access the Internet via the roadside APs. In particular, we focus on one direction of a highway segment and the downlink communications from the AP to a tagged vehicle D. According to the real vehicular traffic trace in [9], the inter-vehicle distance closely follows the exponential distribution. Hence, we assume that the vehicles are spatially distributed along the highway segment as a one-dimensional Poisson point process (PPP) with an intensity function λ (vehicles/m).

To characterize the wireless fading channel in the vehicular environment, we assume that the data transmission between a transmitter located at x and a receiver located at y is subject to Rayleigh fading. That is, the signal-to-noise ratio (SNR) of the received signal can be written as

$$\gamma_{xy} = \frac{P_t}{N_t} h_{xy} g_{xy} \tag{1}$$

where P_t is the transmit power, N_t is the power of additive white Gaussian noise (AWGN), and h_{xy} denotes the small-scale channel fading which is exponentially distributed with unit mean. The path-loss effect is captured by $g_{xy} = \|x - y\|^{-\alpha}$, where $\|x - y\|$ is the Euclidean distance, and α is the path-loss exponent.

Assume that the AP and vehicles adaptively select their modulation modes among binary phase-shift keying (BPSK) and square M-ary quadrature amplitude modulation (M-QAM). The bit error rates (BER) of BPSK and M-QAM are, respectively, given by

$$P_{BPSK} = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{2}$$

$$P_{QAM} = \frac{4}{k}\left(1 - \frac{1}{\sqrt{M}}\right) \text{Q}\left(\sqrt{\frac{3k}{M-1}\frac{E_b}{N_0}}\right) \tag{3}$$

where M is the constellation size, $k = \log_2 M$, and E_b/N_0 is the ratio of bit energy to noise power intensity. Here, $E_b/N_0 = \gamma_{xy} \cdot B_w/R_t$, where B_w is the channel bandwidth (Hz) and R_t is the transmission rate (bps) of the corresponding modulation mode. To successfully decode the received signal, we assume that the BER needs to satisfy a certain requirement. Accordingly, the received SNR should be no less than a threshold β [10]. Hence, the probability of correctly decoding a packet is given by

$$P_{xy} = \Pr\left[\gamma_{xy} \geq \beta\right] = \exp\left(\frac{-\beta}{P_t/N_t}\|x - y\|^{\alpha}\right). \tag{4}$$

B. Problem Formulation

Due to the fast speeds of vehicles and the limited coverage of roadside APs, the direct transmission of a packet from the AP to the tagged vehicle D may fail. Meanwhile, the neighbor vehicles that correctly overhear the packet from the AP can retransmit the packet to D. In general, a centralized relay selection solution aims to identify the best relay(s) by exploiting a global view of the network so as to maximize the transmission success probability and minimize the collision probability. However, because such protocols require additional time to exchange channel state information, the incurred overhead and delay are often large. Hence, we consider an opportunistic V2V relay protocol in this paper.

We assume that each vehicle knows its own location, which can be obtained either from a locating technique based on signal strength or through a GPS receiver which becomes increasingly ubiquitous. Further, the location of the tagged vehicle D can also be piggybacked in the transmitted packet. It should be noted that the AP is unnecessary to know the locations of the surrounding vehicles, and each relay vehicle does not have the location information of others either. As such, each relay vehicle R can estimate its transmission success probability P_{RD} to the destination D according to its location information and (4) and choose its backoff time as

$$W = (1 - P_{RD}) \cdot F \tag{5}$$

where the transmission time of a packet at the highest modulation rate is taken to be one time unit and the maximum backoff time is F time units. It is expected that a good relay vehicle ends up with a short backoff time while there is a small probability that two or more relays time out within an indistinguishable interval c when a collision occurs [11].

Let M_s and M_v denote the constellation sizes of the modulations of the source AP and a relay vehicle, respectively. Given a lower-rate modulation for the AP, more relay vehicles in the vicinity are likely to correctly overhear the packet from the AP and can help forward the packet to D if the direct transmission fails. Thus, there is a larger chance to employ relays closer to D and result in a higher transmission success probability. Meanwhile, with the opportunistic relay protocol, the collision probability will also be higher with more relay candidates. To balance the trade-off, it is important to properly determine the modulation of the source AP (M_s) depending on the spatial distribution of vehicles and the location of the destination vehicle D. On the other hand, a relay vehicle also needs to decide its modulation (M_v) so that a certain transmission success probability is guaranteed while the packet delay is minimized. Clearly, a higher-rate modulation can reduce delay but it is more sensitive to transmission errors.

III. Opportunistic V2V Relay with Adaptive Modulation

Consider K modulation modes for the roadside AP and relay vehicles. Let β_i denote the decoding SNR threshold of the modulation mode i, $i = 1, \ldots, K$. Given that a modulation mode s is adopted by the AP to broadcast a packet to the destination vehicle D, the success probability of the direct transmission is given by

$$P_{SD} = \exp\left(\frac{-\beta_s}{P_t/N_t}L^\alpha\right) \tag{6}$$

where P_t/N_t is the transmit SNR at the AP and L is the distance between the AP and D. Similarly, a neighbor vehicle of a distance r to the AP can correctly overhear the packet with a probability

$$P_{SR}(r) = \exp\left(\frac{-\beta_s}{P_t/N_t}r^\alpha\right). \tag{7}$$

These vehicles that correctly overhear the packet are referred to as *potential relays*. Thus, the spatial distribution of the potential relays can be viewed as the result of a $p(x)$-thinning process [12], where the $p(x)$-thinning is a generalized operation that defines a retention probability $p(x)$ for each point of a PPP and yields a thinned point process by deleting the point with a probability $1-p(x)$. According to Prekopa's Theorem [12], the resulting point process of these potential relays is also a PPP. The intensity measure is given by

$$\Lambda = \int_0^L \lambda P_{SR}(r)\,\mathrm{d}r. \tag{8}$$

When $\alpha = 2$, we obtain the closed-form expression of Λ as

$$\Lambda = \frac{\lambda}{2}\sqrt{\frac{\pi}{K_s}}\mathrm{erf}\left(\sqrt{K_s}L\right) \tag{9}$$

where $K_s = \frac{\beta_s}{P_t/N_t}$. Thus, the probability of having l potential relays is given by

$$\Pr\left[N_r = l\right] = \frac{\Lambda^l}{l!}e^{-\Lambda}, \qquad l = 0,1,2,\ldots \tag{10}$$

A. Statistics of potential relay vehicles

Due to the probabilistic nature of the opportunistic V2V relay protocol, we first analyze the statistics of the potential relay vehicles in terms of their channel conditions, including the average received SNR from a potential relay to the destination D (denoted by $\overline{\gamma}_{RD}$) and the corresponding transmission success probability (denoted by P_{RD}).

According to the channel model in (1), we can write the cumulative distribution function (CDF) of $\overline{\gamma}_{RD}$ as

$$\begin{aligned} F_\gamma(x) &= \Pr\left[\overline{\gamma}_{RD} \le x\right] = \Pr\left[\frac{P_t}{N_t}\|R-D\|^{-\alpha} \le x\right] \\ &= \Pr\left[\|R-D\|^\alpha \ge \frac{P_t/N_t}{x}\right]. \end{aligned} \tag{11}$$

The CDF in (11) depends on the spatial distribution of the potential relay vehicles and it can be further expressed as

$$F_\gamma(x) = \frac{1}{\Lambda}\int_0^L \lambda P_{SR}(r)\cdot \mathbf{1}\left((L-r)^\alpha \ge \frac{P_t/N_t}{x}\right)\mathrm{d}r \tag{12}$$

where $\mathbf{1}(\cdot)$ is the indicator function, given by

$$\mathbf{1}(y) = \begin{cases} 1, & \text{if } y > 0 \\ 0, & \text{if } y \le 0. \end{cases}$$

The ratio in (12) defines the fraction of the potential relays that satisfy the condition $\|R-D\|^\alpha \ge \frac{P_t/N_t}{x}$, for a given average received SNR x. When $\alpha = 2$, a closed-form expression is obtained as

$$F_\gamma(x) = \frac{\lambda}{2\Lambda}\sqrt{\frac{\pi}{K_s}}\mathrm{erf}\left(L\sqrt{K_s} - \sqrt{\frac{K_s P_t/N_t}{x}}\right). \tag{13}$$

Let $G_P(y)$ denote the CDF of the transmission success probabilities of the potential relay vehicles to the destination D. According to (4), we have

$$G_P(y) = \Pr\left[P_{RD} \le y\right] = \Pr\left[\exp\left(\frac{-\beta_v}{P_t/N_t}\|R-D\|^\alpha\right) \le y\right] \tag{14}$$

where β_v is the decoding SNR threshold if the relay vehicle forwards the overheard packet to D using a modulation mode v. Here, $G_P(y)$ in (14) is related to $F_\gamma(x)$ in (11) as follows:

$$\begin{aligned} G_P(y) &= \Pr\left[\frac{P_t}{N_t}\|R-D\|^{-\alpha} \le \frac{-\beta_v}{\ln(y)}\right] \\ &= \Pr\left[\overline{\gamma}_{RD} \le \frac{-\beta_v}{\ln(y)}\right] = F_\gamma\left(\frac{-\beta_v}{\ln(y)}\right). \end{aligned} \tag{15}$$

Based on the estimated transmission success probability, each relay vehicle can determine its backoff time individually according to (5). Then, we can write the CDF of the backoff time of the potential relay vehicles as

$$\begin{aligned} H_W(t) &= \Pr\left[(1-P_{RD})\cdot F \le t\right] = \Pr\left[P_{RD} \ge 1 - \frac{t}{F}\right] \\ &= 1 - G_P\left(1 - \frac{t}{F}\right). \end{aligned} \tag{16}$$

B. Packet delay and success probability

Based on the analysis in Section III-A, we can further evaluate the average packet delay, denoted by $\overline{T}$, and the overall transmission success probability with the opportunistic V2V relay protocol, denoted by P_{suc}.

Since we use the time of transmitting a packet at the highest modulation rate as one time unit, the delay of the direct transmission from the AP to D is then K/s time units if the AP adopts a modulation mode s, where $s = 1,\ldots,K$. Similarly, the transmission time of a relay vehicle to D is K/v time units if the relay applies a modulation mode v, where $v = 1,\ldots,K$. In addition, the relay waits for a random backoff time according to its estimated transmission success probability to D. According to (16), we obtain the mean backoff time as

$$\overline{W} = \int_0^F \left[1 - H_W(t)\right]\mathrm{d}t. \tag{17}$$

The total average packet delay is then

$$\begin{aligned} \overline{T} &= P_{SD}\frac{K}{s} + (1-P_{SD})\left(\frac{K}{s} + \overline{W} + \frac{K}{v}\right) \\ &= \frac{K}{s} + (1-P_{SD})\left(\overline{W} + \frac{K}{v}\right). \end{aligned} \tag{18}$$

The overall transmission success probability depends on the direction transmission and the retransmission via the relay vehicles. Particularly, the retransmission is subject to both fading errors and collision loss. Hence, we have

$$P_{suc} = P_{SD} + (1 - P_{SD})\widetilde{P}_{RD} I_c \tag{19}$$

where I_c is the probability of no collision among the relay vehicles and $\widetilde{P}_{RD}$ is the average transmission success probability of the best relay that wins the contention.

Supposing that there are l vehicles $(l \geq 1)$ that correctly overhear a packet from the AP to D, we have $P_{RD,(1)} < P_{RD,(2)} < \ldots < P_{RD,(l)}$ denote the l order statistics of the transmission success probabilities of these potential relays. According to the opportunistic relay protocol, the best relay has the highest transmission success probability, $P_{RD,(l)}$, and the shortest backoff time. The CDF of $P_{RD,(l)}$ of the best relay among l candidates is given by $\{\Pr[P_{RD} \leq y]\}^l$. Hence, we can obtain the CDF of the highest transmission success probability among a random number of potential relays as

$$\widetilde{G}_P(y) = \sum_{l=1}^{\infty} \frac{\Lambda^l}{l!} e^{-\Lambda} \cdot \left[G_P(y)\right]^l. \tag{20}$$

Thus, the average transmission success probability is given by

$$\widetilde{P}_{RD} = \int_0^1 \left[1 - \widetilde{G}_P(y)\right] \mathrm{d}y. \tag{21}$$

The study of an opportunistic V2V relay protocol in [6] assumes that the priority scheme that determines a random contention window works perfectly. Actually, as discussed in Section II-B, we need to balance the trade-off of engaging more high-quality relays and mitigating their collisions. Given l potential relay vehicles that correctly overhear the packet, we denote the l order statistics of their backoff time by $W_{(1)} < W_{(2)} < \ldots < W_{(l)}$. In [11], the authors derive the joint probability density function (PDF) of the minimum and second minimum of l order statistics as well as the probability that the difference of the minimum and second minimum is greater than a constant. Based on their conclusion, if the difference of the minimum and second minimum backoff time is greater than a constant c, the probability of no collision is given by

$$\begin{aligned} I_c|l &= \Pr\left[W_{(2)} \geq W_{(1)} + c\right] \qquad (22) \\ &= l(l-1)\int_c^F h_W(t)\left[1 - H_W(t)\right]^{l-2} H_W(t-c)\,\mathrm{d}t \end{aligned}$$

where $h_W(t)$ is the PDF corresponding to the CDF in (16). Considering a random number of potential relays, we can obtain the overall probability of no collision as

$$I_c = \sum_{l=1}^{\infty} \frac{\Lambda^l}{l!} e^{-\Lambda} \cdot I_c|l. \tag{23}$$

Then, (21) to (23) can be applied to (19) to evaluate the overall success probability.

As seen from the above analysis, the access performance ($\overline{T}$ and P_{suc}) depends on the modulation mode of the AP for the direct transmission and that of the the relay vehicles for retransmission. The performance is also related to the environment such as the vehicle density. The proposed analysis well characterizes the impact of various aspects of the drive-thru Internet system and can be used to appropriately determine the modulation modes.

TABLE I

SYSTEM PARAMETERS.

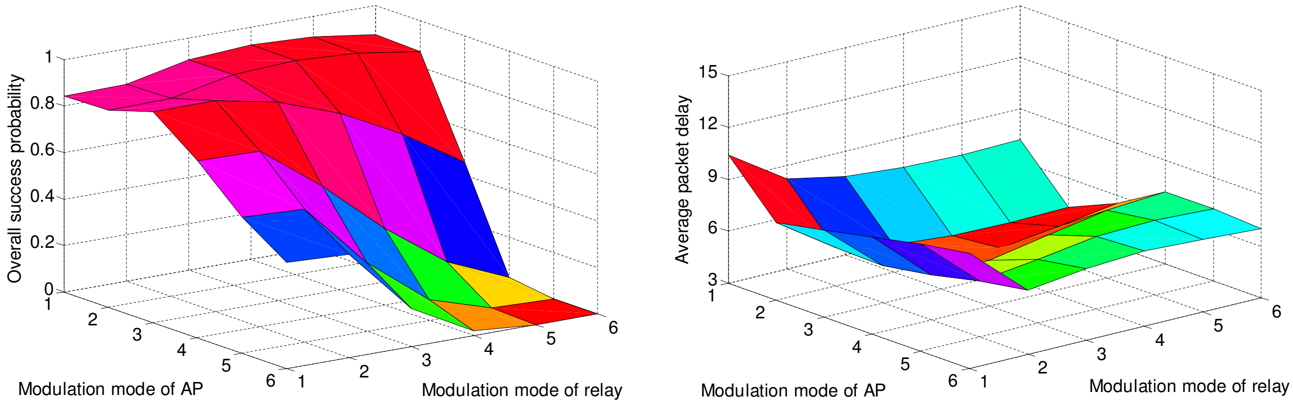
Definition	Symbol	Value
Distance between AP and D	L	1000 m
Channel bandwidth	B_w	22 MHz
Number of modulation modes	K	6
Minimum success probability	P_{suc}	0.8
Collision interval	c	0.01 time units
Maximum backoff time	F	5 time units
Transmit SNR	P_t/N_t	55 dB
Path loss exponent	α	2
Vehicle density	λ	0.05 $\sim$ 0.25 vehicles/m

IV. NUMERICAL AND SIMULATION RESULTS

In this section, we first verify our analysis accuracy with simulations. Then, more experiments are conducted to demonstrate the variation of the access performance with the modulation modes. Last, we show that our analysis can be used to adaptively choose the modulation modes so that the overall success probability is guaranteed while the packet delay is minimized. Both the numerical analysis and computer simulations are conducted with MATLAB 7.14.0 (R2012a) [13]. The system parameters are given in Table I.

Fig. 2 demonstrates the variation of the access performance with the modulation modes of the AP and the relay vehicles. It is shown that our analysis well captures the trade-off between the packet delay and success probability and the performance dependency on the modulation modes.

Fig. 3 compares the analysis results with the proposed approach in Section III to the simulation results against the vehicle density λ. As seen, the analysis and simulation results match well for both the packet delay and success probability. It is worth mentioning that the sudden increase of packet delay is due to more collisions with a larger vehicle density. Based on the analysis in Section III, the best modulation modes can be determined so that a minimum transmission success probability is guaranteed, while the packet delay is minimized. Given a requirement that $P_{suc} \geq 0.8$, Fig. 4 shows the access performance with adaptive modulation modes selected by our analytical approach. Clearly, the overall success probability meets the required minimum bound. In the meantime, the packet delay is even decreasing with a higher vehicle density. This is because the modulation modes can be effectively adapted with our analysis to balance the trade-off between engaging good relay candidates for a higher data rate and more intense collisions with more contending relays.



(a) Overall success probability.

(b) Average packet delay.

Fig. 2. Variation of overall success probability and average packet delay with modulation modes.

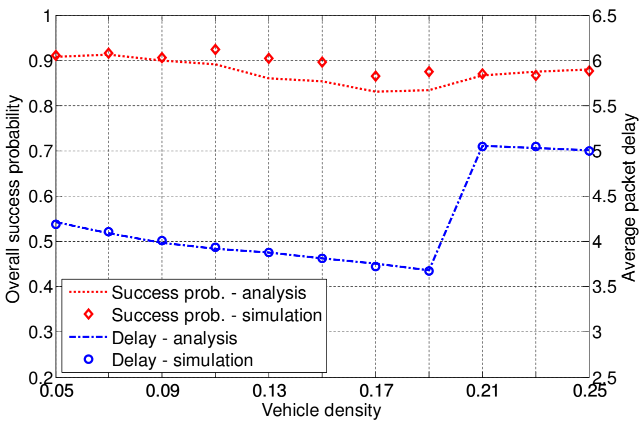


Fig. 3. Analysis and simulation results of overall success probability and average packet delay.

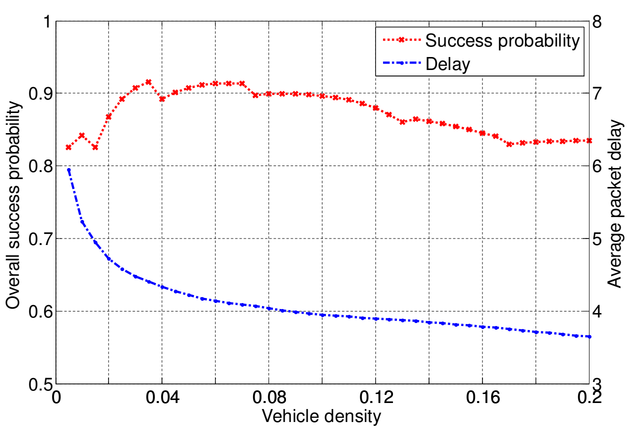


Fig. 4. Overall success probability and average packet delay with modulations adapted with vehicle density.

V. Conclusions

In this paper, we study an opportunistic V2V relay protocol with adaptive modulation to improve the access performance of the drive-thru Internet system. In the proposed protocol, each potential relay vehicle that correctly overhears a packet from the roadside AP to a tagged vehicle independently determines a backoff time according to its estimated transmission success probability to the destination. An analytical approach is developed to evaluate the access performance of the V2V relay protocol in terms of overall success probability and average packet delay. Our analysis captures the dependency of the performance on the modulation modes of the AP and the relay vehicles and other system parameters such as the vehicle density. Based on the analysis, the modulation modes can be adapted according to the environment to guarantee a required transmission success probability while minimizing the average packet delay. The numerical and simulation results demonstrate the accuracy of the analysis and the effectiveness of the proposed solution.

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