Analysis of A Location-Aware Probabilistic Strategy for Opportunistic Vehicle-to-Vehicle Relay

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***Abstract*—Vehicular networks can enable a variety of services to improve safety and comfort for travelling. To mitigate the high cost for deploying dense roadside units (RSUs), vehicle-to-vehicle (V2V) communications can complement vehicle-to-infrastructure (V2I) communications to compensate for intermittent connectivity and enhance transmission performance. In this paper, we analyze a location-aware opportunistic V2V relay scheme in terms of the transmission success probability for a target destination vehicle and the connectivity probability when the scheme is applied to inter-connect adjacent RSUs. The analytical approach based on stochastic geometry captures the effects of key system parameters such as vehicle density, RSU coverage, and modulation schemes. It can be used to adapt the forwarding probabilities of relay vehicles with the network conditions. The numerical and simulation results demonstrate the accuracy of the analysis and the effectiveness of V2V relay scheme.**

***Index Terms*—Vehicular networks, V2V relay, opportunistic relay, connectivity probability.**

I. Introduction and Related Work

With the development of wireless technologies, the wide deployment of vehicular networks is envisioned to enable a variety of services to improve safety and comfort for travelling [1]. In the vehicular network, vehicle-to-infrastructure (V2I) communications via the inter-connected roadside units (RSUs) often only support intermittent connectivity due to coverage limitation and deployment cost. Vehicle-to-vehicle (V2V) communications between onboard units (OSUs) of vehicles can further complement V2I communications to provide ubiquitous coverage. The V2V relay strategy is essential to address the high mobility of vehicles and the limited coverage of RSUs.

In [2], the inter-relay handoff decision problem is investigated for a two-hop vehicular network using a semi-Markov decision process. The optimal handoff decision is derived to maximize the user's overall reward, which captures various factors such as the link transmission rate over the two-hop channel and the handoff overhead. In [3], 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 neighbours to obtain their locations, speeds, directions, and estimated data rates to the RSUs. The relay selection is source-centered and the source basically selects the neighbour vehicle with the highest data rate to an RSU.

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An opportunistic relay protocol is proposed in [4] for the drive-thru Internet. In the opportunistic relay protocol, the RSU 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. 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 [4] may not be able to determine the best broadcast rate, especially for a scenario of a high vehicle density. In [5], we propose an adaptive modulation scheme for V2V relay with opportunistic channel access based on backoff time. We develop an analytical approach that evaluates 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.

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, this paper studies an opportunistic V2V relay protocol so as to improve the access performance of the direct transmission from an RSU (source) to a destination vehicle. Each potential relay vehicle that successfully overhears a packet from the RSU independently determines a random forwarding probability depending on its location information and estimated transmission success probability to the destination. A relay vehicle of a good channel condition to the destination should end up with a high forwarding probability, so that it is prioritized when forwarding the packet to the destination. Moreover, we apply stochastic geometry to analyze the performance of the location-aware probabilistic relay strategy in terms of transmission success probability from an individual vehicle perspective and connectivity probability from the vehicular network perspective. Based on the analysis, we can adapt the forwarding probability with vehicle density and other system parameters. The simulation results validate the accuracy of the analysis and demonstrate the merit of location-awareness in adapting the relay strategy.

The rest of the paper is organized as follows. In Section II, we present the system model under study and the location-aware probabilistic V2V relay strategy. In Section III, we introduce our analysis to determine the forwarding probability and evaluate the performance of the relay strategy. Numerical and simulation results are given in Section IV. Section V concludes this paper.

II. System Model

In this paper, we consider a vehicular network that covers a highway segment as depicted in Fig. 1. In particular, we focus on the downlink communications from the RSU to a tagged vehicle D. According to the real vehicular traffic trace in [6], 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).

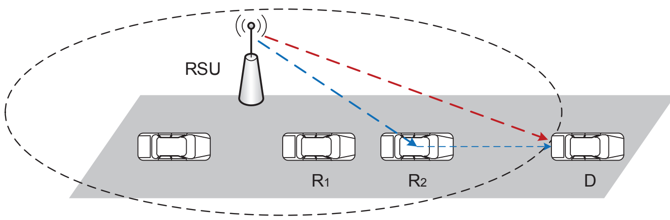

Fig. 1. System model with V2V relay.

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

$$\gamma_{xy} = \frac{P_x}{N_x} h_{xy} g_{xy} \tag{1}$$

where P_x is the transmit power, N_x 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.

To successfully decode the received signal, we assume that the received SNR should be no less than a threshold β [7]. Then, the probability of correct packet decoding is given by

$$P_{xy} = \Pr\left[\gamma_{xy} \geq \beta\right] = \exp\left(\frac{-\beta}{P_x/N_x}\|x - y\|^{\alpha}\right). \tag{2}$$

Due to the fast speeds of vehicles and the limited coverage of RSUs, the direct transmission of a packet from the RSU to the tagged vehicle D may fail. Meanwhile, the neighbour vehicles that correctly overhear the packet from the RSU 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. In [7,8], some probabilistic relay strategies were studied for general wireless networks, in which each relay that correctly overhears a packet independently determines a forwarding probability. The key is how to make use of the local information of relays to appropriately tune the forwarding probability so as to reduce the collision probability and improve the transmission success probability.

III. Location-Aware Probabilistic Strategy for Opportunistic V2V Relay

Assume that there are K possible modulation schemes among binary phase-shift keying (BPSK) and square M-ary quadrature amplitude modulation (M-QAM) for the RSU and relay vehicles to choose from. The bit error rates (BER) of BPSK and M-QAM are, respectively, given by

$$P_{BPSK} = \frac{1}{2}\text{erfc}\left(\sqrt{\frac{E_b}{N_0}}\right) \tag{3}$$

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

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 modulation scheme. To successfully decode the received signal, we assume that the BER needs to satisfy a certain requirement.

Let β_s and β_v denote the decoding SNR threshold for the modulation scheme adopted by the RSU and the vehicle, respectively. The success probability of the direct transmission from the RSU to destination vehicle D is given by

$$P_{SD} = \exp\left(\frac{-\beta_s}{P_s/N_v}R^{\alpha}\right) = e^{-K_s R^{\alpha}} \tag{5}$$

where R is the distance between the RSU and the destination vehicle D, P_s is the RSU's transmit power, and $K_s = \frac{\beta_s}{P_s/N_v}$. Similarly, a neighbour vehicle of a distance r to the RSU can correctly overhear the packet with a probability

$$P_{SR}(r) = \exp\left(\frac{-\beta_s}{P_s/N_v}r^{\alpha}\right) = e^{-K_s r^{\alpha}}. \tag{6}$$

The forwarding from the relay vehicle to the destination vehicle results in a successful transmission with a probability

$$P_{RD}(r) = \exp\left(\frac{-\beta_v}{P_v/N_v}(R - r)^{\alpha}\right) = e^{-K_v (R-r)^{\alpha}}. \tag{7}$$

where $K_v = \frac{\beta_v}{P_v/N_v}$.

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 [9], 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 [9], the number of these potential relays in the resulting point process also follows a Poisson distribution. The intensity measure is given by

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

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

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

Thus, the probability of having l potential relays is given by

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

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

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

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

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

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

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

For a given average received SNR x, (12) defines the ratio of potential relays that satisfy the condition $(R-r)^\alpha \ge \frac{P_v/N_v}{x}$ over all potential relays between the RSU and the destination vehicle. When $\alpha = 2$, a closed-form expression for $F_\gamma(x)$ is derived from (6) and (12), given by

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

Let $G_P(y)$ denote the CDF of the transmission success probabilities of the potential relay vehicles to the destination D. According to (7), we have

$$G_P(y) = \Pr\left[P_{RD} \le y\right] = \Pr\left[\exp\left(\frac{-\beta_v}{P_v/N_v}(R-r)^\alpha\right) \le y\right] \tag{14}$$

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

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

B. Success probability

We assume that each vehicle knows its own location, which can be obtained through a GPS receiver that becomes ubiquitous or a locationing technique, e.g., cooperative localization [10]. Further, the location of the tagged vehicle D can also be piggybacked in the transmitted packet. It should be noted that the RSU is unnecessary to know the locations of the surrounding vehicles, and each relay vehicle does not have the location information of others either.

Consider a location-aware probabilistic relay scheme, in which a potential relay R_i can independently set its forwarding probability ζ_i based on the location information to

$$\zeta_i = \left[G_P(p_i)\right]^{\lceil\Lambda\rceil - 1} \tag{16}$$

where p_i is the local estimate of R_i for its transmission success probability to destination D according to (7). The physical meaning of (16) can be interpreted as follows. Supposing that there are M relays ($M \ge 1$) that correctly overhear the packet, we have $P_{l,(1)} < P_{l,(2)} < \ldots < P_{l,(M)}$ denote the M order statistics of the transmission success probability of these potential relays. Then, a given potential relay R_i has the highest transmission success probability among the M candidates with a probability $\left[G_P(p_i)\right]^{M-1}$. This also means the transmission success probabilities of $(M-1)$ potential relays are all not greater than that of R_i, p_i. Since the relays are not aware of the status of others, the average number of potential relays (i.e., Λ) is used here for approximation.

The success probability of this location-aware probabilistic scheme can be analyzed using stochastic geometry as in [7,11]. To avoid collision, the forwarding succeeds when only one potential relay correctly forwards the packet. Thus, the success probability of the scheme can be expressed as

$$P_{suc}^{loc} = Q_0 \cdot T_1 \tag{17}$$

where Q_0 denotes the occurrence probability that only one potential relay in the region forwards the signal received from RSU S toward destination D, and T_1 is the probability that the transmission through the only relay is successful.

Consider a sufficiently small region between r and $(r+\Delta r)$, $0 \le r \le R$. As there is an infinitesimal impact if a single point is excluded from a continuous space [7], Q_0 for such a small region is equivalent to the probability that there is no potential relay in the small region or all potential relays therein if any remain silent. Revising the notation of ζ_i in (16) to highlight its dependence on a potential relay's location at r, we have

$$\zeta(r) = \left[G_P(e^{-K_v(R-r)^\alpha})\right]^{\lceil\Lambda\rceil - 1} \tag{18}$$

where $(R-r)$ is the distance of the potential relay at location r to the destination. Then, the probability that there is no potential relay or only a silent potential relay in this small region is given by $1 - \lambda\Delta r \cdot P_{SR}(r)\cdot\zeta(r)$. Considering all possible locations between S and D, we obtain

$$\begin{aligned}Q_0 &= \lim_{\Delta r\to 0}\prod_r \left[1-\lambda P_{SR}(r)\zeta(r)\Delta r\right]\\ &= \lim_{\Delta r\to 0}\exp\left\{\sum_r \log\left[1-\lambda P_{SR}(r)\zeta(r)\Delta r\right]\right\}\\ &= \lim_{\Delta r\to 0}\exp\left[\sum_r -\lambda P_{SR}(r)\zeta(r)\Delta r\right]\\ &= \exp\left\{-\int_0^R \lambda P_{SR}(r)\zeta(r)\mathrm{d}r\right\}\\ &= \exp\left\{-\int_0^R \lambda e^{-K_s r^\alpha}\zeta(r)\mathrm{d}r\right\}. \quad (19)\end{aligned}$$

Given that only one potential relay is forwarding, we can derive the success probability of its transmission by

$$\begin{aligned}T_1 &= \int_0^R \lambda P_{SR}(r)\zeta(r)e^{-K_v(R-r)^\alpha}\,\mathrm{d}r\\ &= \int_0^R \lambda e^{-K_s r^\alpha}\zeta(r)e^{-K_v(R-r)^\alpha}\,\mathrm{d}r. \quad (20)\end{aligned}$$

C. Connectivity probability

In the preceding analysis, we focus on the coverage of one particular RSU. During the movement of the vehicles, a destination vehicle needs to handoff between adjacent RSUs to maintain a continuous connection, which is illustrated in Fig. 2. However, due to the limited coverage of RSU and the gap between adjacent RSUs, it is possible that a vehicle may temporarily lose its connectivity even with the help of relay vehicles. Therefore, it is important to evaluate the probability that an arbitrary vehicle can access its nearby RSUs directly or via relay vehicles. This connectivity probability obviously depends on the vehicle density, transmit power, and spacing between adjacent RSUs. Based on such analysis, we can properly determine the required transmit power or RSU spacing according to the vehicle density.

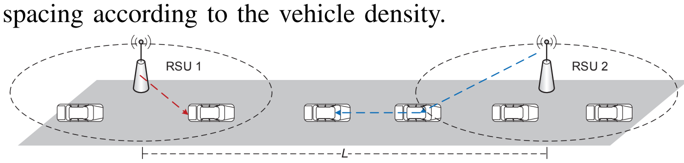

Fig. 2. Connectivity via nearby RSUs or relay vehicles.

Assume that RSUs are deployed along the roadside with an equal distance of L. Then, we can focus on a road segment between two adjacent RSUs. Consider an arbitrary destination vehicle D located at x ($0 \le x \le L$). Since the coverage of RSU depends on its transmit power and modulation/coding scheme, the destination vehicle may be able to access both nearby RSUs, or only one of them, or neither of them. In the last (worst) case, the destination can try to keep connectivity via other relay vehicles. Hence, the connectivity probability of the destination vehicle at x can be expressed as

$$P_{con}(x) = 1-\left[1-P_{dir}(x)\right]\cdot\left[1-P_{rel}(x)\right]) \quad (21)$$

where $P_{dir}(x)$ is the probability that the destination vehicle can access at least one RSU at either end of the road segment, while $P_{rel}(x)$ is the probability that the destination vehicle can connect to one RSU via a relay vehicle.

According to (6), we can easily obtain

$$P_{dir}(x) = 1-\left(1-e^{-K_s x^\alpha}\right)\cdot\left[1-e^{-K_s(L-x)^\alpha}\right]. \quad (22)$$

On the other hand, the connectivity via a relay vehicle requires that at least one relay vehicle should correctly receive the data from at least one RSU at the ends of the road segment, while the relay vehicle should successfully reach the destination vehicle. According to Prekopa's Theorem [9], such relay vehicles that satisfy the above two conditions also follow a Poisson distribution of a mean given by

$$\begin{aligned}\Lambda_{rel} &= \int_0^L \lambda P_{dir}(r)P_{RD}(r)\,\mathrm{d}r\\ &= \int_0^L \lambda P_{dir}(r)e^{-K_v(L-r)^\alpha}\,\mathrm{d}r. \quad (23)\end{aligned}$$

According to the Poisson distribution, the probability that there is no relay vehicle that satisfies the above condition is given by $\exp(-\Lambda_{rel})$. Then, we have

$$P_{rel}(x) = 1-e^{-\Lambda_{rel}}. \quad (24)$$

Substituting (22) and (24) into (21), we can obtain the connectivity probability of the destination vehicle located at x.

Further consider that any arbitrary vehicle along the road segment can be a destination. When there are k vehicles within the road segment, let x_1, x_2, ..., and x_k denote the locations of these k vehicles. Since the vehicles are deployed along the road segment as a PPP, the locations of the k vehicles follow a k-dimensional uniform distribution according to the property of Poisson process. That is, given $x_1 < x_2 < ... < x_k$, these k vehicles are located at $[x_1, x_1+\Delta x_1]$, $[x_2, x_2+\Delta x_2]$, ..., and $[x_k, x_k+\Delta x_k]$, respectively, with a probability given by

$$Y_k(\Delta x_1, \Delta x_2, ..., \Delta x_k) = \frac{1}{L^k}\Delta x_1\cdot\Delta x_2\cdots\Delta x_k. \quad (25)$$

The average connectivity probability of these k vehicles is given by

$$\overline{P}_{con}(k) = \int_{x_1}\cdots\int_{x_k}\frac{1}{k}\sum_{i=1}^k P_{con}(x_i)\cdot\frac{1}{L^k}\,\mathrm{d}x_1\cdots\mathrm{d}x_k. \quad (26)$$

As x_1, x_2, ..., and x_k are symmetric and independent of each other, we can reduce (26) to the following equation:

$$\begin{aligned}\overline{P}_{con}(k) &= \frac{1}{L^k}\cdot\frac{1}{k}\sum_{i=1}^k\int_{x_1}\cdots\int_{x_k} P_{con}(x_i)\,\mathrm{d}x_1\cdots\mathrm{d}x_k\\ &= \frac{1}{L^k}\int_{x_1}\cdots\int_{x_k} P_{con}(x_i)\,\mathrm{d}x_1\cdots\mathrm{d}x_k\\ &= \frac{1}{L^k}\cdot L^{k-1}\int_{x_i} P_{con}(x_i)\,\mathrm{d}x_i\\ &= \frac{1}{L}\int_0^L P_{con}(x)\,\mathrm{d}x. \quad (27)\end{aligned}$$

TABLE I
SYSTEM PARAMETERS.

Definition	Symbol	Value
Distance between RSU and D	R	$0 \sim 2000$ m
Distance between adjacent RSUs	L	$400 \sim 3000$ m
Channel bandwidth	B_w	22 MHz
Number of modulation schemes	K	6
Transmit power of RSUs over noise	P_s/N_v	$40 \sim 56$ dB
Transmit power of vehicles over noise	P_v/N_v	$40 \sim 56$ dB
Path loss exponent	α	2
Vehicle density	λ	0.005$\sim$0.18 veh's/m

As the number of vehicles along the road segment follows a Poisson distribution of a mean λL, we can obtain the overall connectivity probability of any arbitrary vehicle as follows:

$$\begin{aligned}\overline{P}_{con} &= \sum_{k=0}^{\infty} \frac{(\lambda L)^k}{k!} e^{-\lambda L} \cdot \overline{P}_{con}(k) \\ &= \frac{1}{L} \int_0^L P_{con}(x)\, \mathrm{d}x. \end{aligned} \tag{28}$$

IV. NUMERICAL AND SIMULATION RESULTS

In the following, we conduct numerical analysis and computer simulations with MATLAB R2015a. The system parameters are given in Table I. Some parameters are varied to examine their effects on the performance. One one hand, we verify our analysis accuracy with simulations. On the other hand, we evaluate the performance of the location-aware probabilistic relay scheme, referred to as *Probabilistic Location-aware*, and compare it with another relay scheme, referred to as *Probabilistic Constant*. In this reference scheme, each potential relay sets the same forwarding probability (denoted by τ_v) to retransmit the packet. The forwarding is successful if only one potential relay transmits and the transmission to the destination succeeds. Hence, the overall success probability of this reference scheme is given by

$$\begin{aligned}P_{suc}^{cnst} &= P_{SD} + (1 - P_{SD})\overline{P}_{RD} \\ &\quad \cdot \sum_{l=0}^{\infty} \frac{\Lambda^l}{l!} e^{-\Lambda} \cdot C_l^1 \cdot \tau_v \cdot (1-\tau_v)^{l-1} \end{aligned} \tag{29}$$

where Λ is defined in (8) and $\overline{P}_{RD}$ is the average success probability of all potential relays for forwarding, given by

$$\overline{P}_{RD} = \int_0^1 \left[1 - G_P(y)\right] \mathrm{d}y. \tag{30}$$

Here, the last summation term in (29) is the probability that only one potential relay forwards the received packet and thus causes no collision. In (30), the average forwarding success probability $\overline{P}_{RD}$ is derived by taking the integral of the complementary CDF according to (14). Although the forwarding probability τ_v of this scheme can be properly selected to minimize the collision probability, the overall success probability may be low since promising relays with good relay-to-destination channels are not prioritized.

A. Variations of success probability

Fig. 3 compares the success probability of the *Probabilistic Location-aware* scheme with the *Probabilistic Constant* scheme. The forwarding probability τ_v of the *Probabilistic Constant* scheme is adapted with the vehicle intensity λ to maximize the achievable relay success probability. It is seen in Fig. 3 that the analytical results match well the simulation results for the two different schemes. Also, Fig. 3 shows that the *Probabilistic Location-aware* scheme significantly outperforms the *Probabilistic Constant* scheme. When the vehicle density increases, the success probability of the *Probabilistic Location-aware* scheme increases as there are more potential relay vehicles for forwarding and contention is mitigated by setting location-aware forwarding probabilities. In contrast, the success probability of the *Probabilistic Constant* scheme degrades slightly because the intenser contention is not coped with well and results in a higher collision probability. Meanwhile, the *Probabilistic Location-aware* scheme maintains its performance gain over the *Probabilistic Constant* scheme as it can adapt the forwarding probability with the vehicle density.

B. Variations of connectivity probability

In Section III-C, we further analyze the connectivity probability to characterize the impact of RSU deployment on the connectivity performance for vehicles. Fig. 4 shows the analytical and simulation results of the connectivity probability of a destination vehicle located at x, where $0 \leq x \leq L$ and $L = 2000$m is the distance between adjacent RSUs. This connectivity probability $P_{conn}(x)$ can be evaluated by (21). As seen, the analytical results match well the simulation results for different node densities. Intuitively, the middle point of $x = L/2$ has the worst connectivity since it is farthest away from both nearby RSUs. Fig. 4 also demonstrates that the connectivity probability is higher with a larger node density, since the connectivity can be improved through relaying vehicles.

Fig. 5 shows the analytical and simulation results of the connectivity probability of an arbitrary destination vehicle between two adjacent RSUs of a varying spacing L. The connectivity probability is calculated by (28). It is observed that the analytical results are more accurate when the node density is reasonably high, as the randomness effect is more evident with a low density. For fixed transmit powers at the RSUs and vehicles, the connectivity probability degrades with L due to a higher path loss. Meanwhile, the relay vehicles can compensate for the loss of connectivity and achieve a higher connectivity probability with a larger node density.

Fig. 6 shows the analytical and simulation results of the connectivity probability of an arbitrary destination vehicle between two adjacent RSUs of distance $L = 2000$m with varying (P_s/N_v) of RSUs. Similar to Fig. 5, Fig. 6 shows that the connectivity probability increases with the node density. In addition, the connectivity is improved with a higher transmit power of RSUs since a higher transmit power indicates a larger coverage of RSUs. In other words, the spacing between adjacent RSUs can be enlarged if a higher transmit power is allowed with acceptable interference to other systems.

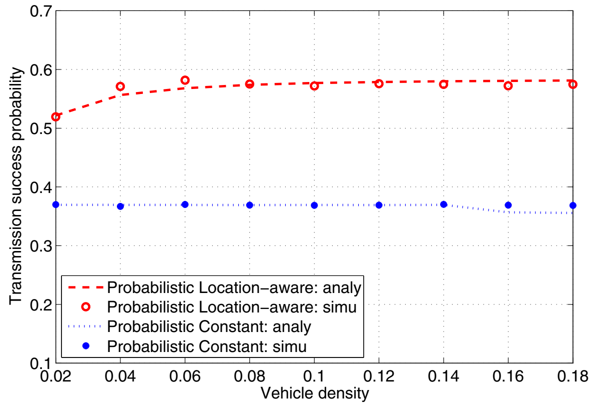

Fig. 3. Comparison of opportunistic relay schemes.

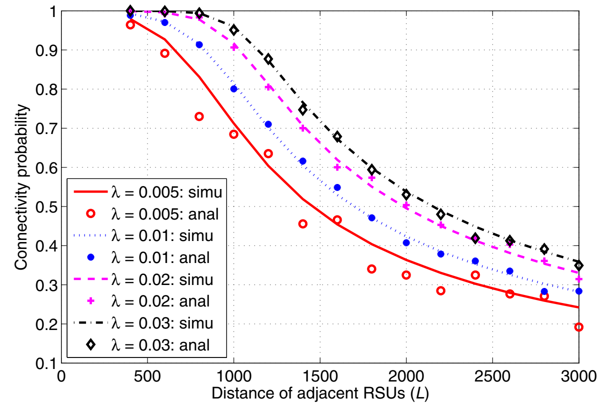

Fig. 5. Connectivity probability vs. distance of adjacent RSUs.

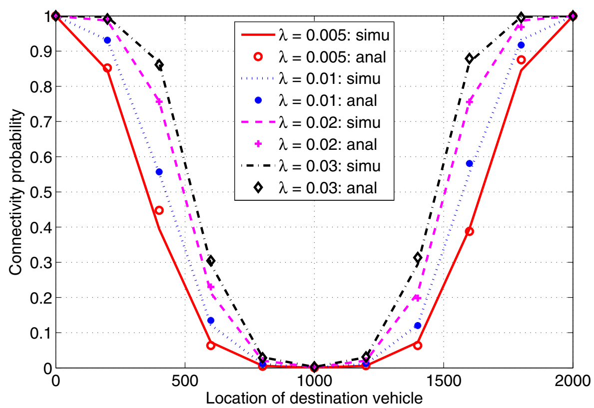

Fig. 4. Connectivity probability vs. location of destination vehicle.

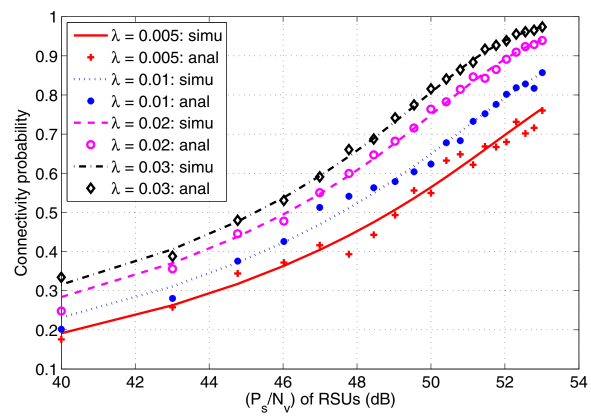

Fig. 6. Connectivity probability vs. (P_s/N_v) of RSUs.

V. Conclusions

In this paper, we study a location-aware opportunistic V2V relay scheme to improve the access performance of vehicular networks. In the proposed protocol, each potential relay vehicle that correctly overhears a packet from the RSU to a tagged vehicle independently determines a forwarding probability according to its estimated transmission success probability to the destination. We apply stochastic geometry to analyze the access performance of the V2V relay protocol in terms of the transmission success probability. The performance depends on system parameters such as vehicle density and RSU's coverage, as well as transmission parameters such as the modulation schemes and decoding thresholds. Furthermore, we investigate the overall connectivity probability of the vehicular network when the proposed V2V relay scheme is employed to inter-connect adjacent RSUs. The simulation results verify the accuracy of the proposed analysis and demonstrate the effectiveness of the location-aware relay scheme.

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