Connectivity Analysis for Cooperative Vehicular Ad Hoc Networks under Nakagami Fading Channel

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***Abstract*—User behaviors like inter-vehicle cooperation have a significant impact on vehicular network connectivity. Intuitively, the network performance can be boosted by introducing cooperation. However, an increasing number of cooperative vehicles may result in increased interference and thus negatively affect the system performance. In this letter, we present an analytical framework to study the impact of the cooperative vehicle ratio on connectivity probability under Nakagami fading channel for both cases of independently non-identically and identically distributed interference. The lower bound of the optimal cooperative ratio is derived to explicitly reveal its relation with system parameters when interference are identically distributed. Numerical results are supplemented by simulations to demonstrate the accuracy of the analytical framework and provide useful guidelines for estimating connectivity performance in the network design for scheduling policy in vehicular networks.**

***Index Terms*—Vehicular ad hoc networks, cooperation, connectivity probability, Nakagami fading.**

I. Introduction

CONNECTIVITY is the fundamental characteristic to determine the performance of end-to-end communication and provide guidance for system configuration in Vehicular Ad Hoc Networks (VANETs). For most vehicular communication services, it is essential to guarantee inter-vehicle connectivity in order to achieve reliable transmissions [1]. Cooperation may encourage more vehicles to act as relays in the multi-hop communication and thus improve inter-vehicle connectivity. Intuitively, increased cooperative vehicles can lead to a broader successful reception range for message dissemination and can enhance connectivity. However, a large number of cooperative vehicles (which may send signals simultaneously at the same frequency band) also increase interference. As a result, connectivity probability will deteriorate due to significant interference when the cooperative ratio exceeds a certain threshold. Therefore, it is of importance to analyze the tradeoff between the cooperative ratio and connectivity probability with regard to interference.

Analysis on vehicular connectivity has attracted lots of attention recently, however small-scale fading in the vehicular environment has been largely neglected in the literature [2]–[5]. Due to the dynamic environment of vehicular communications, small-scale fading has a significant impact on radio propagation and the received signal envelope. We employ the Nakagami distribution to reflect the small-scale fading of vehicular channels, as it is commonly used to characterize small-scale fading [6], and it can also represent some specific situations such as Rayleigh and Rician fading. Moreover, the Nakagami distribution has been proven to fit well to the vehicular channel measurements in [7]–[10].

In this letter, we analyze the tradeoff between the cooperative ratio and connectivity probability under the Nakagami fading channel model, with independently non-identically distributed (non-i.i.d.) and identically distributed (i.i.d.) interference. We firstly derive the closed form expression of connectivity probability for a more general case of non-i.i.d. interference. Then tractable results of connectivity probability for both non-i.i.d. and i.i.d. (which is a special case of non-i.i.d.) are presented and analyzed. Moreover, a lower bound of the optimal cooperative ratio is obtained and its relation with system parameters can be derived under i.i.d. condition. To the best of the authors' knowledge, it is the first time the joint effects of cooperation, interference, and channel fading on the connectivity performance have been evaluated in VANETs.

II. System Model

We consider the same system model in [11] and assume that the vehicles enter the highway according to a Poisson process with intensity λ. For any vehicle, a driver can choose to be cooperative or non-cooperative. Let p_c denote the cooperative ratio. An arbitrary cooperative vehicle can transmit in a given timeslot with the transmission probability p_t. Those active cooperative vehicles (which transmit simultaneously) also lead to significant interference power at the intended receiver.

Random variable N_I denotes the number of interference. According to spatial point process, N_I follows a Poisson distribution with intensity $\widetilde{\lambda} = \lambda p_c p_t$ and can be given by

$$\Pr\{N_I = L\} = \frac{\widetilde{\lambda}^L}{L!} e^{-\widetilde{\lambda}} = \frac{(\lambda p_c p_t)^L}{L!} e^{-\lambda p_c p_t} . \tag{1}$$

We consider the Nakagami distribution to describe small-scale fading characteristics and model the fluctuations of received signal envelopes. Let A denote the received signal envelope from a transmitter, which follows a Nakagami(m_s, ω_s) distribution with the probability density function (PDF)

$$f_A(x;\ m_s,\ \omega_s) = \frac{2{m_s}^{m_s}}{\Gamma(m_s){\omega_s}^{m_s}} x^{2m_s-1} \exp\left(-\frac{m_s}{\omega_s}x^2\right) , \tag{2}$$

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where $0.5 \leq m_s \leq 5$ is the fading parameter of the received signal from the transmitter [7]–[10], ω_s is the mean received power in the fading envelope, and $\Gamma(m) = \int_0^\infty t^{m-1}e^{-t}dt$ is the Gamma function.

The received power ($S = A^2$) from transmitter is Gamma-distributed with the cumulative density function (CDF)

$$\Pr\{S \leq x\} = \frac{\gamma\left(m_s, \frac{m_s}{\omega_s}x\right)}{\Gamma(m_s)} \ , \tag{3}$$

where $\gamma(m,x) = \int_0^x t^{m-1}e^{-t}dt$. In the following, we use notation $S \sim Ga(m_s, \omega_s)$ to represent the received power S in the Gamma distribution with parameters m_s and ω_s.

Random variable I_i denotes the power of i-th interference, for $i = 1, 2, \cdots, L$. Under the Nakagami channel, the power I_i follows a Gamma distribution with parameters m_i and ω_i, respectively, (i.e., $I_i \sim Ga(m_i, \omega_i)$). Hence, the total interference power Y at a receiver is $Y = \sum\limits_{i=1}^{L} I_i$.

Assuming that the white noise power is negligible compared to the power of co-channel interference, we use the signal-to-interference ratio (SIR) to determine the connectivity between the transmitter and the receiver vehicles. When the received SIR exceeds a certain threshold value η, the transmission can be successfully completed, and the link between the transmitter and receiver vehicles is assumed to be connected. Therefore, the connectivity probability P_{con} can be defined as the successful reception probability that SIR at the receiver exceeds the threshold value, and can be calculated as

$$\begin{aligned} P_{con} &= \Pr\left\{\frac{S}{\sum_{i=1}^{L} I_i} \geq \eta\right\} = \Pr\left\{\frac{S}{Y} \geq \eta\right\} \\ &= \sum_{L=1}^{\infty} \Pr\left\{\frac{S}{Y} \geq \eta | N_I = L\right\} \Pr\{N_I = L\} \ . \end{aligned} \tag{4}$$

III. Connectivity Probability

Considering the channel model where interference are non-i.i.d., we employ the discrete distance-dependent model of the m_i-parameter based on the measurements in [7], as depicted in Table I.

$\{a_n\}_{n=1}^N$ is the set of all the possible values of the fading parameter, which corresponds to the distance set $\{D_n\}_{n=1}^N$. For any i-th interference, if the transmission distance $d_i \in (D_{n-1}, D_n], n = 1, 2, \cdots, N$, then the fading parameter $m_i = a_n$. According to the distribution of d_i represented by Eq. (A.1) in Appendix A, we can obtain the probability mass function (PMF) of the fading parameter m_i as follows (the proof can be seen in Appendix A).

$$\begin{aligned} &\Pr\{m_i = a_n\} \triangleq \Pr\{m_i\} \\ &= \begin{cases} \dfrac{1}{(i-1)!}\gamma\left(i, \lambda p_c p_t D_n\right) & n = 1 \\ \dfrac{1}{(i-1)!}\left[\gamma\left(i, \lambda p_c p_t D_n\right) - \gamma\left(i, \lambda p_c p_t D_{n-1}\right)\right] & n > 1 \end{cases} , \\ &\text{for } i = 1, 2, \cdots, L, \ n = 1, 2, \cdots, N \ . \end{aligned} \tag{5}$$

Then the conditional connectivity probability with non-i.i.d. interference is derived as follows:

Theorem 1: Given that the received power from the transmitter is $S \sim Ga(m_s, \omega_s)$, and L non-i.i.d. interference under Nakagami channel are received with distinct interference power $I_i \sim Ga(m_i, \omega_i)$, the conditional connectivity probability is expressed as

$$\Pr\left\{\frac{S}{Y} \geq \eta | L; m_1, m_2, \cdots, m_L\right\} = \psi \sum_{k=0}^{\infty} \delta_k I_\varphi\left(\rho + k, m_s\right) \ , \tag{6}$$

where $\psi = \prod\limits_{i=1}^{L}\left(\frac{\theta_1}{\theta_i}\right)^{m_i}$, $\theta_i = \frac{\omega_i}{m_i}$, $\theta_1 = \min_i\{\theta_i\}$, $\varphi = \frac{1/\theta_1}{1/\theta_1 + \eta m_s/\omega_s}$, $\rho = \sum\limits_{i=1}^{L} m_i$, $I_\gamma(\alpha, \beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\mathrm{B}_\gamma(\alpha, \beta)$ and $\mathrm{B}_\gamma(\alpha, \beta) = \int_0^\gamma t^{\alpha-1}(1-t)^{\beta-1}dt$ is the incomplete beta function, and coefficient δ_k can be recursively calculated by

$$\begin{cases} \delta_0 &= 1 \\ \delta_{k+1} &= \dfrac{1}{k+1}\sum\limits_{s=1}^{k+1}\left[\sum\limits_{j=1}^{L} m_j\left(1 - \dfrac{\theta_1}{\theta_j}\right)^s\right]\delta_{k+1-s} \\ & \quad k = 0, 1, 2, \cdots \end{cases} . \tag{7}$$

Proof: Given that there are L independently non-identically gamma-distributed interference, using the sum of gamma variables [12], [13], the PDF of the total interference power Y at the receiver is expressed as

$$f_Y(y) = \psi \sum_{k=0}^{\infty} \frac{\delta_k y^{\rho+k-1} e^{-\frac{y}{\theta_1}}}{\theta_1^{(\rho+k)}\Gamma\left(\rho+k\right)} \ . \tag{8}$$

Combining Eq. (3) and (8), the conditional connectivity probability is calculated as

$$\begin{aligned} &\Pr\left\{\frac{S}{Y} \geq \eta | L; m_1, m_2, \cdots, m_L\right\} \\ &= \psi \sum_{k=0}^{\infty} \frac{\delta_k \int_0^\infty \Gamma\left(m_s, \frac{m_s}{\omega_s}\eta y\right) y^{\rho+k-1} e^{-\frac{y}{\theta_1}} dy}{\theta_1^{(\rho+k)}\Gamma\left(\rho+k\right)\Gamma(m_s)} \ , \end{aligned} \tag{9}$$

where $\Gamma(m,x) = \int_x^\infty t^{m-1}e^{-t}dt$ is the complementary incomplete gamma function.

According to the Eq. (6.455.1), (8.391) and (9.131.1) in [14], the integral in the numerator above is reducible as:

$$\int_0^\infty \Gamma\left(\nu, \alpha x\right) x^{\mu-1} e^{-\beta x} dx = \frac{\Gamma(\mu+\nu)}{\beta^\mu}\mathrm{B}_{\frac{\beta}{\alpha+\beta}}(\mu, \nu) \ . \tag{10}$$

Then we obtain the result in Eq. (6), which can be simplified as $\psi \sum\limits_{k=0}^{\infty} u_k$, where $u_k = \delta_k I_\varphi\left(\rho+k, m_s\right)$. When $\rho \leq 1$, we have $\lim\limits_{k\to\infty} |\delta_k|^{1/k} < 1$ and (6) converges. If $\rho > 1$, (6) also converges due to the uniform convergence of (8) in [13]. ■

Therefore, based on the law of total probability, the connectivity probability is expressed as

$$\begin{aligned} P_{con} &= \sum_{L=1}^{\infty}\sum_{m_i}\Pr\left\{\frac{S}{Y} \geq \eta | L; m_1, \cdots, m_L\right\}\Pr\{L; m_1, \cdots, m_L\} \\ &= \sum_{L=1}^{\infty}\sum_{m_i}\Pr\left\{\frac{S}{Y} \geq \eta | L; m_1, \cdots, m_L\right\}\Pr\{N_I = L\}\prod_{i=1}^{L}\Pr\{m_i\} \ . \end{aligned} \tag{11}$$

The connectivity probability can be numerically calculated by substituting (1), (5) and (6) into (11). In practice, the number of interference L is limited, and when L exceeds a certain threshold M^1, the term of series in Eq. (11) approaches to 0 and can be negligible. Therefore, Eq. (11) is approximate to a finite sum of M terms and has a polynomial computational complexity in the order of M^5, denoting $O(M^5)$, which can be well controlled within a given limit.

In order to further explore insight relations between connectivity, optimal cooperative ratio and system parameters, we consider the special case when the interference have i.i.d. statistic, thus any received power I_i is a Gamma distributed random variable with the same fading parameter m and mean power ω, that is $I_i \sim Ga(m,\omega)$. Hence the total interference power Y also follows a Gamma distribution ($Y \sim Ga(mL,\omega)$) and the PDF is given by

$$f_Y(y;\ m,\ \omega,\ L) = \left(\frac{m}{\omega}\right)^{mL} \frac{y^{mL-1}}{\Gamma(mL)} \exp\left(-\frac{m}{\omega}y\right) \ . \quad (12)$$

Then we derive the conditional connectivity probability with i.i.d. interference as follows:

Corollary 1: Given that the received power from the transmitter is $S \sim Ga(m_s,\omega_s)$ and total interference power is $Y \sim Ga(mL,\omega)$, the conditional connectivity probability is expressed as

$$\Pr\left\{\frac{S}{Y} \geq \eta | N_I = L\right\} = I_\xi(mL, m_s) \ , \quad (13)$$

where $\xi = \dfrac{m/\omega}{m/\omega + \eta m_s/\omega_s}$.

The result can be deduced as a special case of Eq. (6) and keeps in agreement with [15].

Substituting Eq. (1) and (13) into (4), the connectivity probability in the case of identically gamma-distributed interference can be numerically obtained by

$$P_{con} = \sum_{L=1}^{\infty} I_\xi(mL, m_s) \frac{(\lambda p_c p_t)^L}{L!} e^{-\lambda p_c p_t} \ . \quad (14)$$

Similarly, the number of interference L is generally limited in the case of i.i.d. interference. Considering that Eq. (14) is approximate to a finite sum of M terms, the computational complexity of (14) is linear with M, denoting $O(M)$.

The lower bound of the optimal cooperative ratio is derived in the following corollary:

Corollary 2: For the optimal cooperative ratio p_c^* in (14), that is $p_c^* = \arg\max_{p_c} P_{con}(p_c)$, its lower bound $p_{c_{low}}^*$ follows

$$p_{c_{low}}^* \in \Omega\left(\frac{1}{\lambda p_t}\right) \ , \quad (15)$$

where Ω is the Big Omega Notation.

Proof: The optimal cooperative ratio p_c^* of (14) satisfies:

$$f'(p_c^*) = \sum_{L=1}^{\infty} \frac{\widetilde{\lambda^*}^{L-1}}{L!} I_\xi(mL, m_s)(L - \widetilde{\lambda^*})\lambda p_t e^{-\widetilde{\lambda^*}} = 0. \quad (16)$$

[1]The value of M is determined by the network scale, topology and radio conditions, etc, which is out of the scope of this paper.

TABLE I
DISCRETE DISTANCE-DEPENDENT MODEL OF m_i-PARAMETER

d_i	$\leq D_1$	$\leq D_2$	$\cdots$	$\leq D_n$	$\cdots$	$\leq D_N$
m_i	a_1	a_2	$\cdots$	a_n	$\cdots$	a_N

As $I_\xi(mL, m_s)$ decreases with L and approaches 0, there exists a positive integer L' satisfying $I_\xi(mL', m_s) \cong 0$. For any integer $\bar{L} > L'$, $\dfrac{\widetilde{\lambda^*}^{\bar{L}-1}}{\bar{L}!} I_\xi(m\bar{L}, m_s)(\bar{L} - \widetilde{\lambda^*}) \cong 0$, then the terms of $f'(p_c^*)$ decrease and approach 0. We can obtain that

$$\begin{aligned} I_\xi(m, m_s) &\approx \sum_{L=1}^{L'-1} \frac{\widetilde{\lambda^*}^L}{L!} \left[I_\xi(mL, m_s) - I_\xi\left(m(L+1), m_s\right)\right] \\ &\leq \sum_{L=1}^{L'-1} \frac{\widetilde{\lambda^*}^L}{L!} \Delta I_\xi \approx \left(e^{\widetilde{\lambda^*}} - 1\right) \Delta I_\xi \ , \end{aligned} \quad (17)$$

where $\Delta I_\xi = \max_{L \in [1,L']} \{I_\xi(mL, m_s) - I_\xi\left(m(L+1), m_s\right)\}$. As $\widetilde{\lambda^*} = \lambda p_c^* p_t$, we can have $p_c^* \geq p_{c_{low}}^*$, where $p_{c_{low}}^* = \dfrac{1}{\lambda p_t} \ln\left(\dfrac{I_\xi(m, m_s)}{\Delta I_\xi} + 1\right)$. The fading parameter in a realistic scenario is set to be $m \in [0.5, 5]$, then we have the bound $\ln\left(\dfrac{I_\xi(m, m_s)}{\Delta I_\xi} + 1\right) \in [1.4, 1.82]$. Hence, $\exists$ positive $k > 0, \forall\lambda, \forall p_t,\ p_{c_{low}}^* \geq k\dfrac{1}{\lambda p_t}$. ■

We can learn from (15) that increasing λ or p_t will negatively affect the optimal p_c^*, and thus the vehicles intend to act less cooperatively in order to improve the connectivity.

IV. NUMERICAL AND SIMULATION RESULTS

We investigate the connectivity probability P_{con} as the function of the cooperative vehicle ratio p_c for both cases of non-i.i.d. and i.i.d. interference. Extensive Monte Carlo simulations are conducted to validate the analytical results of P_{con} and evaluate the impact of p_c. The simulation parameters are set as follows: $\eta = 3$ dB, $p_t = 0.05$, $m_s = 5$, $\omega_s = 1$, $m = 0.5$, $\omega = 0.2$, $\{a_n\} = \{1, 0.5\}$, and $\{D_n\} = \{80, 200 \text{ meters}\}$.

The numerical and simulation results of P_{con} with non-i.i.d. and i.i.d. interference are depicted in Fig. 1 and Fig. 2, respectively. The simulation results are marked with circles and are reasonably close to the theoretical results. The curves in both figures have similar trends. In addition, the connectivity in non-i.i.d. case is slightly worse than in the i.i.d. case, due to the complex features of interference. Furthermore, we can observe from both figures that an increasing p_c can significantly improve connectivity probability until the optimal value p_c^*, and the connectivity would deteriorate when $p_c > p_c^*$. Fig. 3 shows optimal cooperative ratio p_c^* in both cases of i.i.d. and non-i.i.d. interference, and it is found that the optimal cooperative ratio is decreasing with increasing intensity λ and transmission probability p_t. Moreover, it can be seen that the lower bound is tightly close to the optimal cooperative ratio.

From the above analysis we learn that even though we expect that a large number of cooperative vehicles would increase the number of available nodes in VANETs and thus improve the connectivity performance, it is only true

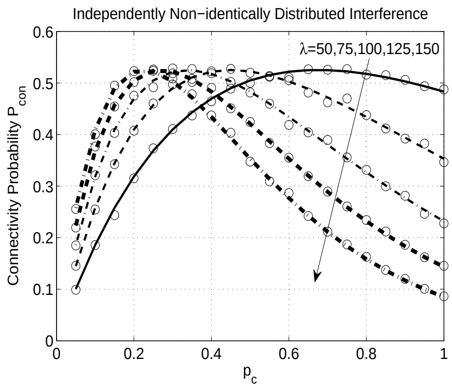

Fig. 1. Connectivity with non-i.i.d. interference.

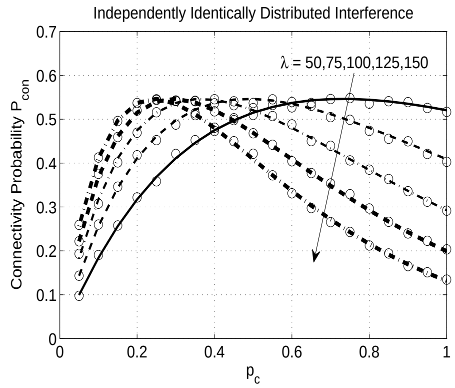

Fig. 2. Connectivity with i.i.d. interference.

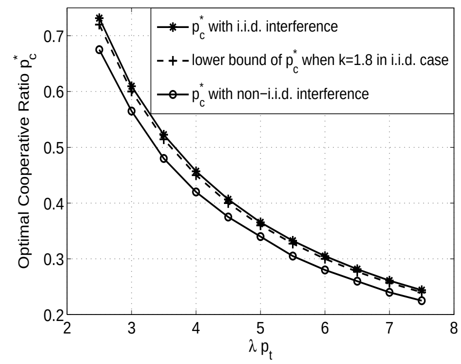

Fig. 3. Optimal cooperative ratio p_c^* vs. λ and p_t.

within a certain region of the cooperative ratio; otherwise, the performance will be negatively affected by the overwhelming interference caused by an increasing number of transmission vehicles. This result should be emphasized when designing vehicular networks, and the interference caused by large numbers of cooperative vehicles should be carefully evaluated.

V. Conclusion

We evaluate the connectivity probability of vehicular networks under the Nakagami fading channel model. Specifically, the exact analytical results have been derived, for the cases of identically and non-identically distributed interference, respectively. We learn that the cooperative ratio plays an important role in the connectivity performance and the interference significantly affects the successful reception of inter-vehicle transmission, hence reasonable MAC protocols should be developed for VANETs to avoid inter-vehicle interference. The overall results in this letter shed light on the effects of the cooperative ratio on connectivity and provide guidance for designing wireless vehicular networks of high performance.

Appendix A
Probability Mass Function of Fading Parameter

According to the stochastic process theory, since the number of interference follows a Poisson distribution with intensity $\widetilde{\lambda}$, then the distance spacing s_k between any k-th interference and its adjacent preceding interference is i.i.d. in exponential distribution with parameter $\widetilde{\lambda} = \lambda p_c p_t$. Thus the PDF of distance spacing s_k can be expressed as $f_{s_k}(x) = \lambda p_c p_t e^{-\lambda p_c p_t x}$.

The transmission distance d_i from any i-th interference to the receiver can be represented by $d_i = \sum\limits_{k=1}^{i} s_k$. As s_k is an independent random variable, the PDF of d_i can be calculated by the i-fold convolution of the PDF of s_k, as follows

$$f_{d_i}(x) = f_{s_1}(x) * \cdots * f_{s_i}(x) = \frac{x^{i-1}}{(i-1)!} (\lambda p_c p_t)^i e^{-\lambda p_c p_t x} \ . \tag{A.1}$$

Based on the corresponding relation between the transmission distance d_i and the fading parameter m_i of the i-th interference signal in Table I, we can have $\Pr\{m_i = a_1\} = \Pr\{d_i \le D_1\} = \int_0^{D_1} f_{d_i}(x)dx = \frac{1}{(i-1)!}\gamma\left(i, \lambda p_c p_t D_1\right)$. Similarly, when $D_{n-1} < d_i \le D_n$, $n > 1$, we can obtain $\Pr\{m_i = a_n\} = \Pr\{D_{n-1} < d_i \le D_n\} = \int_{D_{n-1}}^{D_n} f_{d_i}(x)dx = \frac{1}{(i-1)!}\left[\gamma\left(i, \lambda p_c p_t D_n\right) - \gamma\left(i, \lambda p_c p_t D_{n-1}\right)\right]$.

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