Perception-Connection Tradeoff for Radar Cooperative Sensing in Multi-hop Vehicular Networks

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Abstract. With radar cooperative sensing, vehicles can not only leverage their own radar to perceive the road condition ahead but also establish a connection with vehicles in front to obtain environment information farther away. In this paper, a radar cooperative sensing scheme based on multi-hop for vehicular networks is proposed for far-reaching perception. Vehicles on the road perform radar sensing while conducting multi-hop communication with front ones to obtain road information outside the LOS range. In order to streamline hardware equipment and deal with the upcoming shortage of spectrum resources, each vehicle is equipped with TD-JRC to realize both radar sensing and communication function within the same frequency band. Besides, we design a resource allocation strategy for this cooperative sensing system, numerical and simulation results show that there is indeed a optimal joint power and time allocation strategy to realize the maximized average RCSCR for a definite vehicle density.

Keywords: V2V · Cooperative sensing · Joint radar-communication · Resource allocation

1 Introduction

In order to achieve high-level autonomous driving, in addition to using the autonomy of the vehicle, the collaborative perception between vehicles is used to share detected obstacles or perception data and expand their perception range, thereby improving their situational awareness ability and driving safety [5].

The realization of collaborative perception requires vehicles on the road to have both radar sensing and data communication capabilities. In the past

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research on vehicle network, radar sensing and communication modules used separately designed hardware devices, occupying an isolated section of spectrum resources respectively. With the exponential growth of wireless devices and data traffic, the spectrum becomes more and more scarce, and the limited spectrum resources will affect the radar's sensing and data communication performance in the near future.

At the same time, the development of signal process technology as well as hardware design ability make radar and communications are developing in the direction of joint design. Benefiting from the high similarity of radar and communication function in respect of transceiver design, antenna structure and working bandwidth, it is glad to see the joint design of these two systems is available [12]. Therefore, by using unified hardware equipment and spectrum resources, spectrum reuse can be used to alleviate the limitations caused by the shortage of spectrum resources, which is also known as joint radar communication (JRC) technology. The specific implementation of JRC has a time, frequency, beam sharing scheme [8], joint wave design [11], etc.

For autopilot, achieving far-reaching perception through the connection between adjacent vehicles can not only achieve better safety and decision-making capacity than the autonomy of a vehicle but also improve traffic throughput and fuel economy through global route optimization and cooperative driving [4].

To realize this vision, it is necessary to have both strong radar sensing capability and communication connection capability. In the power-constrained JRC system, the tradeoff of Radar perception and communication ability is essential. Increasing radar perception ability will inevitably reduce communication performance and vice versa. A reasonable resource allocation strategy can maximize the range of vehicle cooperative perception and provide a sufficient decision-making basis for safe and reliable autonomous driving.

In order to cope with this challenge, in this paper, we studied how the joint time and power distribution strategy of the time-division joint radar-communication (TD-JRC) system affects the radar cooperative sensing range under different vehicle densities.

Numerical and simulation results show that there is indeed an optimal time and power allocation strategy to maximize the radar cooperative sensing range by leveraging a priori vehicle density information.

2 System Model

2.1 Network Module

In Fig. 1, vehicles with perceptive ability distribute on two lanes with opposite directions of travel. Each vehicle in two lanes has the same dynamic characteristics as well as sensor configurations. Therefore, throughout this paper we focus on one of the road lanes for research conciseness.

Assuming the number of vehicles per unit distance follows the one-dimensional Poisson Process with density ρ as Poisson distribution provides a

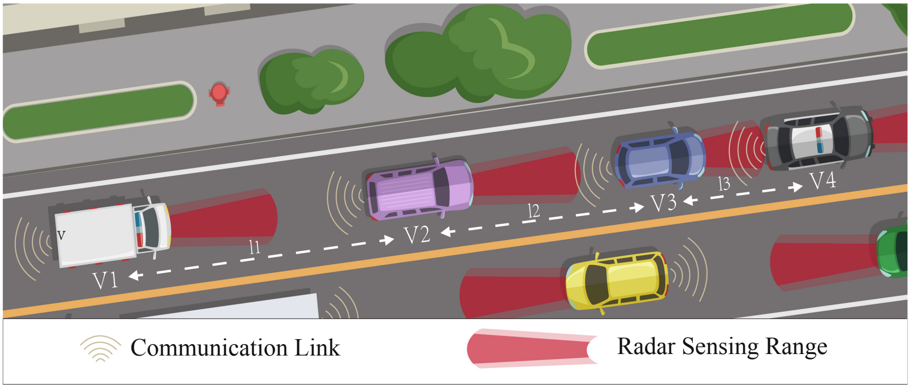

Fig. 1. Radar cooperative sensing in multi-hop vehicular network

practical model for the arrival process of vehicles. Since the number of vehicles follows the Poisson distribution, the distance between two adjacent vehicles can be obtained according to the exponential distribution [7] and the Probability Density Function (PDF) of adjacent vehicles interval l is

$$f_L(l) = \rho e^{-\rho l} \tag{1}$$

For safety requirements, the vehicles interval have to satisfy one preset minimum distance d_{min}, and the distance between a pair of adjacent vehicles is distributed randomly from the minimum distance to infinity, such that using truncated Gaussian probability density function to describe the vehicle interval will make the research results more in line with the actual situation. The revised PDF of vehicles interval from l_{min} to infinity is given as

$$\tilde{f}_L(l) = \frac{\rho e^{-\rho l}}{\int_{l_{min}}^{+\infty} \rho e^{-\rho l} dl} = \frac{\rho e^{-\rho l}}{e^{-l_{min}\rho}} \tag{2}$$

and the corresponding cumulative distribution function (CDF) is

$$\tilde{F}_L(L < l) = 1 - \int_l^{\infty} \tilde{f}_L(l) dl \tag{3}$$

Each vehicle implemented a set of TD-JRC systems at the front and rear to perform radar and communication functions, which sharing the identical Millimeter-wave frequency band, and the conversion between two functions carry out in a time-division manner.

Due to the attenuation characteristics of millimeter waves, assuming vehicles can only establish a connection directly with their neighbor nodes in line-of-sight (LOS) channel, i.e., adjacent ones in front of or behind it, by vehicle-to-vehicle (V2V) link. For nodes out of sight, vehicles establish links via multi-hop by treating nodes within the LOS range as relay nodes. e.g., in Fig. 1, $V2$ has the capability of connecting with $V1$ or $V3$ in a direct link. Nevertheless, blocked by $V3$, $V2$ can not connect with it unless $V3$ acts as a relay node.

With the help of communication links and multi-hop transmission, vehicles can obtain road information far beyond their perceptual coverage. In-vehicle intelligence will benefit from the richer perceptual information to make more accurate and timely decisions.

In this paper, we propose the radar cooperative sensing covered range (RCSCR) of one vehicle to measure the performance of radar cooperative sensing, which is defined as the sum of received forward sensing information covered range perceived by the JRC system implemented in forwarding vehicles and its own.

Besides, we design a joint distribution strategy of power and time for radar sensing and communication function, the objective of such strategy is to maximize average RCSCR for vehicles in the research road with vehicle density ρ.

For the TD-JRC we used, the first part of a frame is used to realize the radar sensing mode while the second part is used to realize the communication mode. The total power of the JRC system is P_s, Limited by the hardware structure, the power distribution between radar and communication are independent of each other.

First, the TD-JRC system works in radar mode and continuously perceives road information ahead, and then, the system work converts to communication mode, receiving perceive information from adjacent vehicles in direct communication and outrange ones in multi-hop.

It is worth noting that the sensing information is transmitted at most one hop within one frame. Considering the time validity of the information and reducing the communication burden of the system, the sensing information that fails to be transmitted will not be retransmitted. In other words, for frame duration T, the information transmitted through N hops from the source node to destination node will elapse a duration of NT. Considering the moving speed of vehicles and transmission hop number, both of which are usually a small value, this transmission delay can be sufficiently short to be thought of as insignificant, so it is reasonable to treat the information transmitted through multi-hop as realtime.

2.2 Radar Model

To achieve better radar cooperative sensing performance, one needs to fully understand the capabilities and characteristics of vehicle-mounted radars. In most application scenarios, the maximum detection range is an essential tactical and technical indicator of radar, and the detection range of the radar is a statistical concept as there is randomness noise in the radar system. The radar equation [9] reflects the relationship of parameters related to the detection range, which is given as

$$R_{max} = \left[\frac{P_t G_t G_r \lambda^2 \sigma}{(4\pi)^3 k T_s F B_n D(m)} \right]^{1/4} \tag{4}$$

where σ represents radar cross-section (RCS), which is not the physical area of the target but reflects the ability of the target to reflect signal power, P_t denotes radar transmit power, G_t is transmit gain, G_r indicates receive gain, F is noise coefficient, B_s represents the system bandwidth for both radar and communication function, $\lambda = c/f_s$ is the carrier wavelength with c and f_s being the speed of light and carrier frequency, respectively, k is Boltzmann constant, T_s indicates the system noise temperature, $D(m)$ is Radar detection factor according to pulse accumulation number $m = \lfloor \tau f_r \rfloor = \lfloor \frac{\tau}{T_r} \rfloor$, which is the number of radar pulses in a time frame.

Where τ is the duration of radar mode within on frame, f_r and T_r represents radar pulse frequency and cycle, respectively.

In order to expand the detection range of the radar, with most instances, accumulation operations can be performed between pulses to improve the signal-to-noise ratio (SNR) of signal output, if m equal-amplitude coherent signals are coherently accumulated, ideally, the accumulated signal-to-noise ratio will be improved by m times. At this time, the value of detect factor D will decrease. Therefore, the maximum radar sensing range is related to the number of pulse accumulation m.

In actual traffic conditions, the characteristics of vehicles are not only constant RCS, but are usually modeled as random RCS models. Swerling II is a typical RCS model which can be used to characterize target fluctuations [6].

According to [2], the detect probability P_d for Swerling II is

$$\begin{aligned} P_d &= 1 - \frac{1}{(m-1)!} \int_0^{V_T/(1+s)} r^{m-1} e^{r} \, \mathrm{d}r \\ &= 1 - P_\gamma \left(\frac{V_T}{s+1}, m \right) \end{aligned} \tag{5}$$

in which s indicates the SNR at the input of the detector, which can be thought as detect factor, essentially. $P_\gamma(x, y) = \int_0^{x\sqrt{y}+1} e^{-t} t^y / (y!) dt$ is incomplete gamma function and the detection threshold V_T can be expressed by the inverse function of the incomplete gamma function as

$$V_T = P_\gamma^{-1} \left(1 - P_{fa}, m\right) \tag{6}$$

So the detect factor of m cumulative pulses is derived as

$$D(m) = \frac{P_\gamma^{-1} \left(1 - P_{fa}, m\right)}{P_\gamma^{-1} \left(1 - P_d, m\right)} - 1 \tag{7}$$

where P_{fa} denotes radar false alarm probability that the system can tolerate.

It can be concluded from the above analysis that the maximum sensing range of the radar can be calculated based on the preset detection and false alarm probability under the premise that the relevant parameters are already available.

2.3 Connection Analysis

Vehicle connectivity is the crucial foundation of vehicular cooperative sensing, and only when vehicles are connected through V2V link, the perception data can be shared successfully.

In this section, the connection probability of a pair of adjacent vehicles under Rayleigh fading is discussed and the closed-form is provided.

Consider a pair of communication nodes, when the received SNR exceeds a certain threshold $\varPhi$, it is reasonable to assume the signal can be decoded correctly at receiver [10] and this pair of nodes can be thought of as connected.

Let Pr_c denotes the connect probability of two consecutive vehicles, i.e., the probability of received SNR at V_n sent by V_{n-1} exceed the threshold $\varPhi$. In what follows, the Pr_c at a distance d is derived.

The average SNR at distance d can be computed by

$$\overline{\gamma}_c(d) = \frac{G_t G_r \beta P_c}{d^2 P_{cn}} \tag{8}$$

By considering Rayleigh fading as the small-scale fading model, the connection analysis will be more realistic, and the received SNR under Rayleigh fading can be estimated according to the exponential distribution with a mean of average SNR. The PDF of received SNR at a distance d is given as

$$f_\varGamma(\gamma_c(d)) = \frac{1}{\overline{\gamma}_c(d)} e^{-\frac{\gamma_c(d)}{\overline{\gamma}_c(d)}} \tag{9}$$

The corresponding CDF of (12) is given as

$$\begin{aligned} F(\varGamma_c(d) < \gamma_c(d)) &= 1 - e^{-\frac{\gamma_c(d)}{\overline{\gamma}_c(d)}} \\ &= 1 - e^{-\frac{d^2 P_{cn} \gamma_c(d)}{G \beta P_c}} \end{aligned} \tag{10}$$

in which $\varGamma_c(d)$ is the random variable of the receiver SNR in communication process with a distance d.

Therefore, the successful connection probability is expressed as

$$\begin{aligned} Pr_c(d) &= Pr[\varGamma_c(d) > \varPhi] \\ &= 1 - Pr[\varGamma_c(d) < \varPhi] \\ &= e^{-\frac{d^2 P_{cn} \varPhi}{G \beta P_c}} \end{aligned} \tag{11}$$

Constraint by the safe distance d_{min} of vehicle interval, The expectation of successful communication probability within the entire road with vehicle distribution $\tilde{f}_L(l) = \frac{\rho e^{-\rho l}}{e^{-l_{min} \rho}}$ is given as

$$\begin{aligned} Pr_{con} &= \mathbb{E}[Pr_c(L)] \\ &= \int_{d_{min}}^{+\infty} Pr_c(x) \tilde{f}_L(x) dx \\ &= \frac{\rho}{e^{-l_{min} \rho}} \int_{d_{min}}^{+\infty} e^{-(\frac{d^2 P_{cn} \varPhi}{G \beta P_c} + \rho x)} \end{aligned} \tag{12}$$

the closed-form of (12) is shown at the top of this page due to space constraint.

It is worth noting that Pr_{con} is the connective probability only suit for one hop, when there are N hops between source and destination node, the end-to-end connective ability is $Pr_N = pr_{con}^N$ as the interval distance of any pair of adjacent vehicles is independent.

$$\begin{aligned} Pr_{con} &= \int_0^{+\infty} Pr_c(x)f(x)dx - \int_0^{d_{min}} Pr_c(x)f(x)dx \\ &= \frac{\rho}{e^{-l_{min}\rho}} \left\{ \frac{e^{\frac{\beta G P_c \rho^2}{4\Phi P_{cn}}} \sqrt{\pi} Erfc(\frac{\rho}{2\sqrt{\frac{\Phi P_n}{\beta G P_c}}})}{2\sqrt{\frac{\Phi P_n}{\beta G P_c}}} \right. \\ &\left. - \frac{e^{\frac{\beta G P_c \rho^2}{4\Phi P_{cn}}} \sqrt{P_c G \beta \pi}[-Erf(\frac{\sqrt{\beta G P_c}\rho}{2\Phi P_{cn}})] + Erf(\frac{2d_{min}\Phi P_{cn} + \beta G P_c \rho}{2\sqrt{\beta G \Phi P_{cn} P_c}})]}{2\sqrt{\Phi P_n}} \right\} \end{aligned} \tag{13}$$

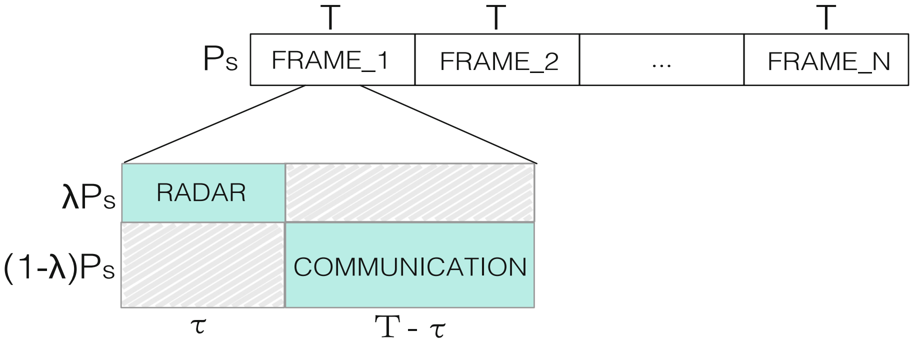

Fig. 2. Joint time and power allocation strategy

3 Perception-Connection Tradeoff

For the proposed radar cooperative sensing scheme, our objective is to maximize the average RCSCR by adjusting the power distribution coefficient $\lambda \in [0, 1]$ and radar sensing duration $\tau \in (0, T]$, with T being the total duration of one frame. The resource allocation strategy is shown in Fig. 2. Under this allocation strategy, the TD-JRC system work in radar mode with power $P_r = \lambda P_s$ within the duration τ, in remainder of one frame, the system work in communication mode with power $P_c = (1 - \lambda)P_s$.

It should be highlighted that the resource allocation scheme we proposed is not for any specific JRC hardware, but for the entire vehicle.

As described in Sect. 2.1, two same JRC hardwares are equipped at the front and rear of the vehicle, performing forward perception-connection and backward perception-connection, respectively. In the proposed cooperative sensing scheme, the JRC at the front of a vehicle is responsible for perceiving road information and receiving the perception information acquired from the adjacent vehicle in front, at the same time, the task of the other one JRC at the rear of the vehicle is to send the combination perception information of the received and its own to the adjacent rear vehicle.

From the above analysis, most of the power allocated to JRC equipped at the front is used for radar perceptive and most of the power allocated to JRC equipped at the rear is used for communication with adjacent one, therefor the radar power consuming at rear and communication power consuming at the front are small enough to be ignored.

To further improve cooperative sensing ability, in the remainder of this section, we will derive how the joint power and time allocation strategy influence the average RCSCR.

Let $\Xi(l)$ be the actual perception range for a vehicle with a distance of l from the car in front. When the vehicle interval is less than the maximum perception range of the radar R_{max}, the actual perception range is equal to vehicle interval due to being blocked by vehicle ahead [1], correspondingly, when there is no vehicle block, the actual perception range is R_{max}, i.e., $\Xi(l) = Min(R_{max}, l)$.

The expectation of radar actual perception range is given as

$$\begin{aligned}\mathbb{E}(\Xi(L)) &= \tilde{F}_L(L > R_{max})R_{max} + \int_{R_{min}}^{R_{max}} \tilde{f}_L(l)ldl \\ &= e^{-\rho R_{max}}R_{max} + \frac{e^{-\rho R_{min}}(1+\rho R_{min}) - e^{-\rho R_{max}}(1+\rho R_{max})}{\rho}\end{aligned} \tag{14}$$

It is unrealistic for the vehicle to connect to all the nodes in front, and the number of vehicles involved in one cooperative process is related to channel capacity and radar data generation data. Let η denotes the volume of data generated per second from radar. The involved vehicle number N for a cooperative process is given as

$$N = \frac{(T-\tau)C}{\eta\tau} \tag{15}$$

with C being the ergodic channel capacity [3], which is given as

$$C = B_s \int_{d_{min}}^{\infty} \tilde{f}_L(l)log(1 + \overline{\gamma}_c(d)) \tag{16}$$

The main objective of the radar cooperative sensing scheme we proposed is to maximize the average RCSCR, which is derived as follows.

$$\begin{aligned}\mathbb{E}(RCSCR) = \mathbb{E}(&\Xi(L_1) + \Xi(L_2)Pr_c(L_1) + \Xi(L_3)Pr_c(L_2)Pr_c(L_1) \\ &+ \cdots + \Xi(L_{N+1})Pr_c(L_N)Pr_c(L_{N-1})\cdots Pr_c(L_1))\end{aligned} \tag{17}$$

As the vehicle interval between different pair of vehicles is independently identically distribution (iid), (17) can be organized as

$$\begin{aligned}\mathbb{E}(RCSCR) &= \mathbb{E}(\Xi(L)) + \mathbb{E}(\Xi(L))\mathbb{E}(Pr_c(L)) + \mathbb{E}(\Xi(L))\mathbb{E}(Pr_c(L)) \\ &\quad \mathbb{E}(Pr_c(L)) + \cdots + \mathbb{E}(\Xi(L_N))\underbrace{\mathbb{E}(Pr_c(L))\mathbb{E}(Pr_c(L))\cdots\mathbb{E}(Pr_c(L))}_{N} \\ &= \mathbb{E}(\Xi(L))(1 + \mathbb{E}(Pr_c(L)) + \mathbb{E}^2(Pr_c(L)) + \cdots + \mathbb{E}^N(Pr_c(L))) \\ &= \mathbb{E}(\Xi(L))\frac{1-\mathbb{E}^N(Pr_c(L))}{1-\mathbb{E}(Pr_c(L))} \\ &= \mathbb{E}(\Xi(L))\frac{1-Pr_{con}^N}{1-Pr_{con}}\end{aligned} \tag{18}$$

It can be seen from (18) that the more time and power allocated to radar, the much more sensing range it will have, and at the same time, power and time allocated to communication mode will be reduced, resulting in connection probability decrease. In other words, the improvement of radar sensing capability is achieved by sacrificing communication efficiency and vice versa.

In order to maximize the average objective function, it is necessary to configure the time and power allocation factors reasonably according to the vehicle density, so as to achieve a tradeoff between the radar function and the communication function.

4 Numerical Results and Simulations

In this section, numerical and simulation results will be presented to verify the proposed cooperative sensing scheme and the relationship between system performance and resource allocation strategy. Unless otherwise specified, we set $\Delta T = 4$ ms as time duration for one frame, total power of radar and communication functions is set to $P = 500$ mw, as the TD-JRC is implemented, both communication and radar function work at $f_s = 77$ GHz with $B_s = 200$ MHz, the generation rate of radar sensing data is set as $\eta = 10$ Mbits/s, for driving safety, the minimum distance between vehicles under extreme situation is set as $l_{min} = 10$ m. Other parameters are set as $k = 1.38 \times 10^{-23}$ J/K, $T_s = 293$ K, $G = G_t G_r = 30$ db, $\beta = 0.5$, $\sigma = 1\text{m}^2$, $F = 0.4$, $p_d = 0.99$, $P_{fa} = 0.01$, $T_r = 100$ µs. The communication channel considers both large-scale path loss and small-scale Rayleigh fading, and the radar sensing channel is considered to conform to the large-scale fading model.

In the beginning, numerical results and Monte Carlo simulation results are provided to verify the theoretical analysis drawn in the previous sections, and for each power allocation factor λ, 2000 times Monte-Carlo calculation are conducted. Figure 3 illustrates the relation between power allocation factor and average RCSCR with the fixed $\tau = 2$ ms and $\rho = 13 \times 10^{-3}$. The cures show that the numerical results and Monte Carlo simulation results are matched to each other, which verifies the correctness of the derivation process. The curves

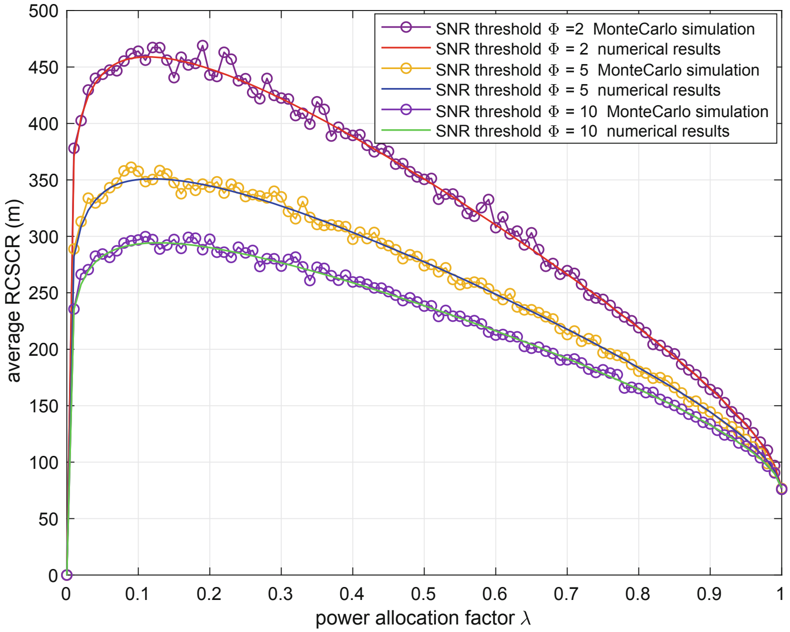

Fig. 3. Relation between average RCSCR and power allocation factor λ with $\tau = 2$ ms, $\rho = 13 \times 10^{-3}$

with different SNR have similar trends, and as Φ decreases, the maximum average RCSCR, i.e., the highest point of each curve, will increase.

Figure 4 illustrates how the allocation strategy of time and power influence the average RCSCR in the form of three-dimensional (3D) graph with vehicle density $\rho = 1 \times 10^{-3}$, 3×10^{-3}, 8×10^{-3} and 25×10^{-3}, respectively. It is obviously seen from results that the vehicle density will greatly affect the power and time allocation scheme. Specifically, when vehicle density is 1×10^{-3}, a relatively low-density state for vehicles on the road, either time or power resource is allocated to radar mode to a large extent. In contrast, when vehicle density is 30×10^{-3}, a relatively high-density state for vehicles on the road, either time or power resource is allocated to communication function to a large extent. When the vehicle density is 3×10^{-3} or 8×10^{-3}, the allocation of resources is relatively balanced, and there is no apparent trend. This is because when vehicles are in a low-density state, the distance between adjacent vehicles is very large. The establishment of a link connection requires a lot of resources and the probability of success is low. The performance gain brought by the exchange of sensor information is very minimal. In this state, the resources of the system are mainly allocated to the radar function to enhance vehicle's own perception ability. When the vehicle is in a high-density state, correspondingly, vehicle's own perception ability is blocked by the preceding vehicle and will not continue to increase with the increase of power and perception time. Therefore, allocating more time and power resources to the communication function will greatly increase the performance of cooperative perception.

Note that regardless of the vehicle density, there is a definite power allocation strategy to maximize average RCSCR under a given vehicle density.

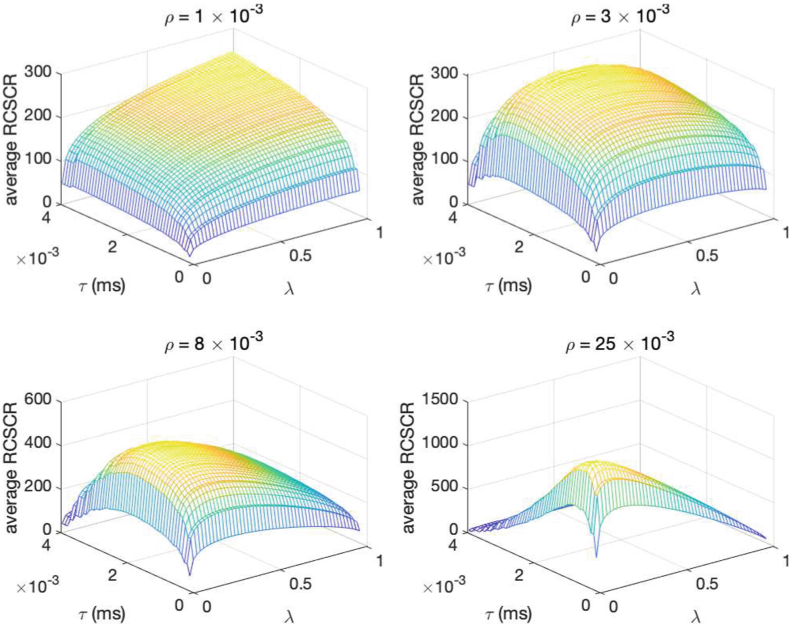

Fig. 4. Relation between average RCSCR and radar sensing time τ as well as power allocation factor λ with $\rho = 1 \times 10^{-3}, 3 \times 10^{-3}, 8 \times 10^{-3}, 25 \times 10^{-3}$, respectively

Figure 5 illustrates the change of the optimal power distribution factor with the vehicle density. It can be seen that in the case of $\tau = 0.2$ ms, 0.5 ms and 2.1 ms, as the vehicle density increases, the power distribution factor gradually decreases. That is, the power allocated to the radar function decreases and the power allocated to the communication function increases, which is consistent with the previous analysis. When $\tau = 3.7$ ms, the optimal power allocation factor will no longer change with the vehicle density but always be 1. In other words, all of the power is allocated to the radar to enhance vehicle's own perception ability. This is because when $\tau = 3.7$ ms, most of the time is allocated to the radar function, and the throughput of the time left for the communication function is not enough to support one-hop communication transmission, that is to say, at this time, the system completely relies on its own radar to realize perception.

Figure 6 illustrates the achievable perception range gain g_p with the proposed radar cooperative sensing scheme under different vehicle density ρ. The benchmark for comparison is the relatively smaller of average vehicle interval $\overline{L} = 1/\rho$

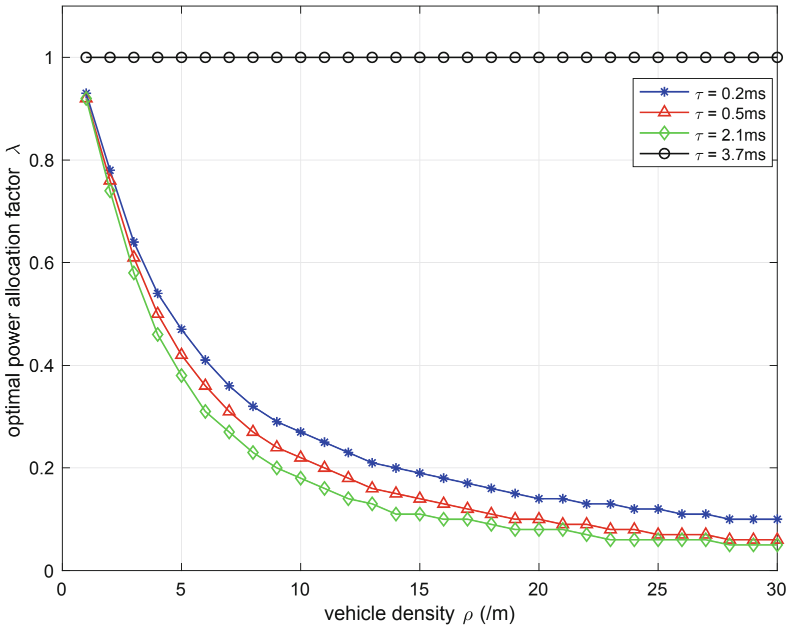

Fig. 5. Relation between vehicle density ρ and the most optimal power allocation factor λ with $t = 0.2, 0.5, 2.1, 3.7$, respectively

and the maximize radar detection range R_{max}, i.e.,

$$g_p = \frac{RCSCR}{min\{\overline{L}, R_{max}\}} \tag{19}$$

For a certain ρ, g_p increases with the decrease of SNR threshold Φ. With lower Φ, vehicles are more likely to establish connections with adjacent vehicles and share perception data. We observe in our simulation that When the vehicle density ρ is greater than 5×10^{-3}, our proposed resource allocation strategy begins to play a significant role, and as the density of vehicles increases, the effect of perception gain become more and more prominent.

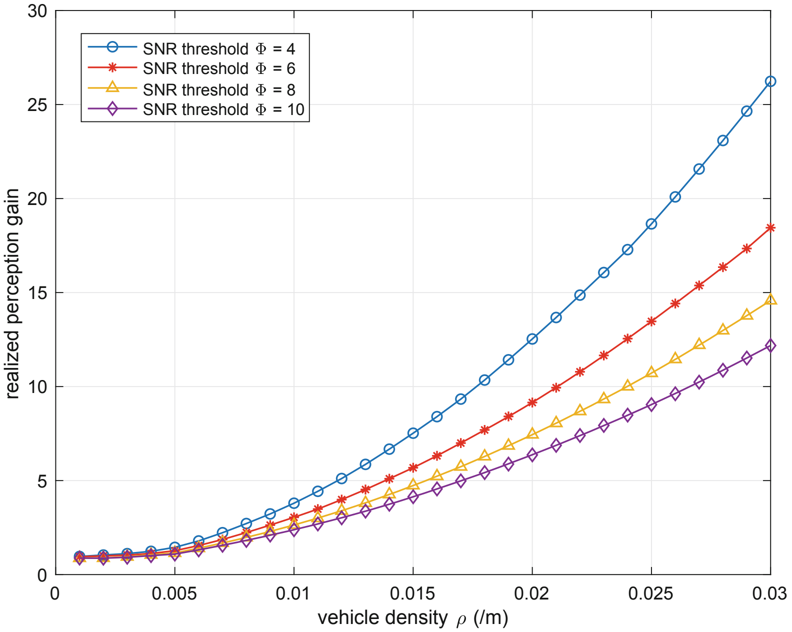

Fig. 6. The relation between realized perception gain and vehicle density ρ

5 Conclusion

This paper has proposed a novel JRC-based radar cooperative sensing scheme for the vehicular network by multi-hop. Through this scheme, vehicles can obtain perceptual information far beyond the range of their own perceptual ability covered. In addition, we focused on analyzing the impact of joint time and power allocation strategy on the performance of the average RCSCR. Numerical and simulation results have proved that for a specific vehicle density ρ, there is a definite joint time and power allocation strategy that maximizes average RCSCR.

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