ISAC Beamforming in Connected Autonomous Vehicles

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Abstract. Connected Automated Vehicles (CAV) is a promising application for connected vehicles. However, in the automatic driving scenario, the sensor blind area will lead to serious security risks, and the existing vehicle-to-vehicle technology is difficult to break through the sensor blind area and ensure the reliability of the perceptual information. To overcome these problems, based on Integrated sensing and communication (ISAC) technology, it is feasible to treat infrastructure as a means to extend the sensing range. The base station transmits a number of beams, including a sensing beam and a communication beam. The sensing beam is responsible for sensing the target in the sensing blind area, and the communication beam is responsible for transmitting the sensed information to the CAV. However, there may be interference in the transmission process. In this paper, the beamforming algorithm of communication beam and sensing beam is designed to reduce the interference, and the communication signal-to-noise ratio (SINR) at the autonomous vehicle and the sensing signal-to-noise ratio (SNR) returned at the base station are guaranteed.

Keywords: Integrated Sensing And Communication · Connected Automated Vehicles · Beamforming

1 Introduction

With the development of the fifth generation of mobile communication, the sixth generation of mobile communication and artificial intelligence technology, the autonomous vehicle industry is developing rapidly. Autonomous vehicles need continuous real-time sensing of the surrounding environment, but it is difficult to achieve it only by on-board functions, because the sensing function of autonomous vehicles is mainly realized by multiple on-board sensors. Under the influence of obstacles and bad weather, vehicles often have a sensing blind area, which will lead to the self-driving car can not obtain a full range of perceptual information, and it is impossible to predict the possible danger. In addition, the

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data format of each sensor on the car is not uniform, and it is difficult to process a large number of sensor data for the vehicle computing system [6].

Beamforming technology is a multi-channel signal processing method that generates synthetic beams through the combination of multiple antennas to improve the performance of the system. Its basic principle is to make the radiation direction of the synthetic beam point to the target. By using this technology, the detection range and anti-interference ability of the system can be improved, and the mutual interference between receivers can be significantly reduced, so a higher signal-to-noise ratio can be obtained. In recent years, the application of beamforming technology in the integration of communication perception [1] has also received a lot of attention. While solving the shortage of wireless communication spectrum resources, beamforming design can be used to reduce the impact of interference. In the scenario of vehicle networking in this subject, the application of this technology can also effectively improve the accuracy of sensing information and expand the range of sensing. The introduction of tradeoff factors can also effectively balance communication performance and sensing performance.

In recent years, efficient sensor data sharing between vehicles through integrated communication and sensing systems has become the key to improving the performance and safety of autonomous driving [5], and this scheme has attracted wide attention. With the progress of technology, many technologies have emerged to realize the integrated function of communication sensing, such as using radar detection information to assist millimeter wave communication [4], embedding communication data in radar signals to design integrated communication sensing waveform [2], and designing integrated communication perception function based on IEEE 802.11ad standard [3].

Based on the above beamforming technology and integrated sensing and communication technology, the main research content of this paper is the research of joint communication and perceptual beamforming algorithm based on ISAC in the scenario of networked autonomous driving, with the purpose of achieving maximum communication SINR at the user and maximum sensing SNR at the base station.

The rest of this paper is organized as follows. In Sect. 2, the system model used in this paper is introduced, in Sect. 3, the beamforming algorithm for joint sensing and communication is designed, and in Sect. 4, the simulation results and analysis are given.

2 System Model

The system model considered in this paper is five autonomous vehicles on a road, two base stations are placed 50 m away from the autonomous vehicle, and there is a sensing blind area 60 m away from the base station, as shown in the Fig. 1 below. In the downlink, assuming that M_t access points are sending communication and sensing beams to jointly serve U users, and M_r access points are used to receive beams sent or reflected by various targets and users in the environment, M_t and M_r can have no overlap, partial overlap or complete overlap.

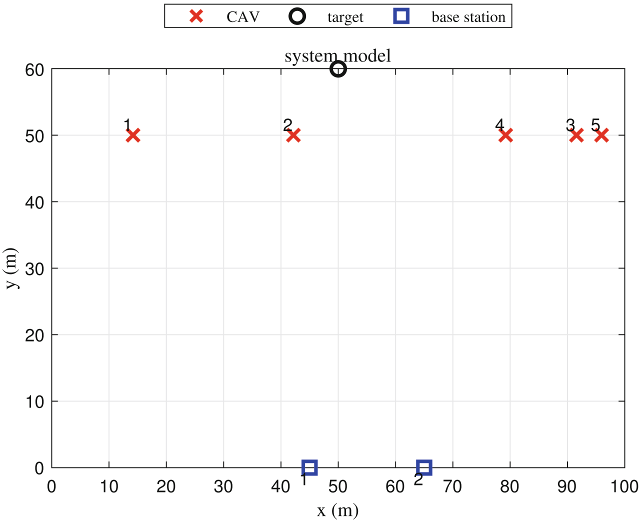

Fig. 1. System model

There are N_t antennas for transmitting and N_r antennas for receiving, assuming that each antenna has a dedicated RF link, that is, each access point has digital beamforming capability.

2.1 Signal Model

The base station transmits the communication beam and the sensing beam, Communication beam $\{x_u[l]\}_{u\in U}$, sensing of beam is $\{x_q[l]\}_{q\in Q}$, then send signals with beam forming vector can be expressed as

$$x_m[l] = \sum_{u\in U} f_{mu}x_u[l] + \sum_{q\in Q} f_{mq}x_q[l] = \sum_{s\in S} f_{ms}x_s[l] \tag{1}$$

The power of the beamforming vector is limited by the total power constraint P_m, There is the following formula

$$E\left[\|x_m[l]\|^2\right] \leq P_m \tag{2}$$

In the following calculation process, the beamforming vectors are stacked into matrix form.

2.2 Communication Model

Assume that the channel between the base station and the self-driving car remains constant during signal transmission. Next, considering a block fading channel model. Then the received signal at CAV can be expressed as

$$y_u[l] = \sum_{m \in M_t} h_{mu}^H x_m[l] + n_u \tag{3}$$

By further dividing the signal part into the communication beam for this vehicle, the communication beam for other vehicles and the sensing beam, the formula can be further transformed into

$$y_u[l] = \sum_{m \in M_t} h_{mu}^H f_{mu} x_u[l] + \sum_{u^* \in U u^* \neq u} \sum_{m \in M_t} h_{mu}^H f_{mu^*} x_{u^*}[l] + \sum_{q \in Q} \sum_{m \in M_t} h_{mu}^H f_{mq} x_q[l] + n_u[l] \tag{4}$$

$n_u[l] \sim CN\left(0, \sigma_u^2\right)$ is receiver noise at CAV, so we can calculate the SINR at CAV

$$SINR = \frac{\left|h_u^H f_u\right|^2}{\sum\limits_{u^* \in U, u^* \neq u} \left|h_u^H f_{u^*}\right|^2 + \sum\limits_{q \in Q} \left|h_u^H f_q\right|^2 + \sigma_u^2} \tag{5}$$

2.3 Sensing Model

The following formula is adopted in this paper for the sensing channel between transmitting sensor beam and receiving echo of the base station

$$G_{m_t m_r} = \alpha_{m_t m_r} a\left(\theta_{m_r}\right) a^H\left(\theta_{m_t}\right) \tag{6}$$

$\alpha_{m_t m_r} \sim CN\left(0, \zeta_{m_t m_r}^2\right)$ is combined sensing channel gain, The effects of path loss and RCS are included, $a\left(\theta\right)$ represents the array response vector. θ_{m_t} and θ_{m_r} represents the Angle of transmitting beam and receiving beam of the base station respectively. Therefore, the echo signal received at the base station can be expressed as

$$y_{m_r}[l] = \sum_{m_t \in M_t} G_{m_t m_r} x_{m_t}[l] + n_{m_r}[l] \tag{7}$$

$n_{m_r}[l]$ is noise at the receiving end of the base station, obey the $CN\left(0, \zeta mr^2\right)$ distribution. First, the vector is compressed into the matrix form $F_m = [f_{m_1}, \ldots, f_{m_s}]$, $X = [x_1, \ldots, x_s]$, $N_{m_r} = [n_{m_r}[1], \ldots, n_{m_r}[L]]$, and then the sensor SNR is represented as

$$SNR = \frac{\sum_{m_r \in M_r} \sum_{m_t \in M_t} \zeta_{m_t m_r}^2 \left\|a^H\left(\theta_{m_t}\right) F_{m_t}\right\|^2}{\sum_{m_r \in M_r} \zeta_{m_r}^2} \tag{8}$$

The above formula is derived from the original definition by F norm expansion, expectation and multiple trace operations [1].

3 Beamforming Algorithm Design

3.1 Optimization Problem Modeling

The main method to be designed in this paper is to jointly optimize communication and sensing beams, The goal is to maximize sensing SNR and communication SINR. Therefore, the optimization problem can be modeled as the following formula

$$\max_{f_{ms}} SNR \tag{9}$$

$$s.t. SINR_u \geq \gamma, \forall u \in U \tag{10}$$

$$\sum_{s \in S} \left\| f_{ms} \right\|^2 \leq P_m, \forall m \in M_t \tag{11}$$

The objective function of the desired solution is non-convex, so consider transforming this problem into a semidefinite programming problem, and then apply semidefinite relaxation to the non-convex objective function to transform the non-convex problem into a convex problem, and further use a convex solver to solve this problem(Table 1).

In order to transform the above problems into semi-definite programming problems, the beamforming vector is first redefined as $F_s = f_s f_s^H$, This form of construction can eliminate the influence of quadratic terms in SNR and SINR. However, the construction of this formula introduces two new constraints: (1) Semi-definite constraint of Hermitian matrix $F_s \in S^+$; (2) Rank-1 constraint $rank\left(F_s\right) = 1$.

For ease of calculation, artificial definition

$$D_{m_t} = \ diag\left(d_{m_t}\right) \otimes I^{N_t \times N_t} \tag{12}$$

$$A = aa^H \tag{13}$$

$d_m = [d_{m1}, \ldots, d_{mM_t}]$, $d_{mm} = 1, d_{mm'} = 0$, $\forall m, m' \in M_t, m \neq m'$, moreover $a = \left[a\left(\theta_1\right)^T, \ldots, a\left(\theta_{M_t}\right)^T\right]^T$, Based on these variables, the objective function sensing SNR can be rerepresented as

$$SNR = \frac{\sum_{m_r \in M_r} \sum_{m_t \in M_t} \zeta_{m_t m_r}^2 Tr\left(D_{m_t} A D_{m_t} \sum_{s \in S} F_s\right)}{\sum_{m_r \in M_r} \zeta_{m_r}^2} \tag{14}$$

For constraints in optimization problems, define $Q_u = h_u h_u^H$. Therefore, the communication SINR can be reformulated as

$$SINR = \frac{Tr\left(Q_u F_u\right)}{\sum_{u^* \in U, u^* \neq u} Tr\left(Q_u F_{u^*}\right) + \sum_{q \in Q} Tr\left(Q_u F_q\right) + \sigma_u^2} \tag{15}$$

Therefore, the optimization problem can be further transformed into

$$SINR_u = \frac{Tr\left(Q_u F_u\right)}{\sum_{u^* \in U, u^* \neq u} Tr\left(Q_u F_{u^*}\right) + \sum_{q \in Q} Tr\left(Q_u F_q\right) + \sigma_u^2} \tag{16}$$

Therefore, this paper further deforms the constraint conditions, and the optimization problem after transformation can be obtained as

$$\max_{\{F_s\}} SNR \tag{17}$$

$$s.t. \left(1+\gamma^{-1}\right) Tr\left(Q_u F_u\right) - Tr\left(Q_u \sum_{s\in S} F_s\right) \geq \sigma_u^2 \tag{18}$$

$$\sum_{s\in S} Tr\left(D_m F_s\right) \leq P_m, \forall m \in M_t \tag{19}$$

$$rank\left(F_s\right) = 1, \forall s \in S \tag{20}$$

$$F_s \in S^{+}, \forall s \in S \tag{21}$$

Therefore, algorithm can be used to solve this problem.

3.2 Joint Sensing and Communication Beamforming Algorithm

Table 1. Joint Sensing and Communication Beamforming Algorithm

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Algorithm: Semi-definite Relaxation Algorithm for Joint Sensing and Communication(JSC) Beamforming
Input: $N_t$, $N_r$, $M_t$, $M_r$
Initialization: $F_u$ and $F_q$
1. for rep=1:n
2. Generate user, target, and base station locations
3. Calculate communication SINR and sensing SNR using (5) and (8)
4. Formulate the joint optimization problem (9) to (11)
5. Transform into the semi-definite programming problem shown in (17) to (21)
6. Relax the rank-1 constraint in (20)
7. Solve the semi-definite programming problem using convex optimization toolbox CVX
8. Apply eigenvalue decomposition to generate an approximate optimal solution for the original optimization problem
9. end
Output: $F_u$ and $F_q$
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4 Simulation Result

In this section, we consider the effects of different number of antennas and different number of users on the designed algorithm when the proportion of communication power to total power ranges from 0 to 1 respectively.

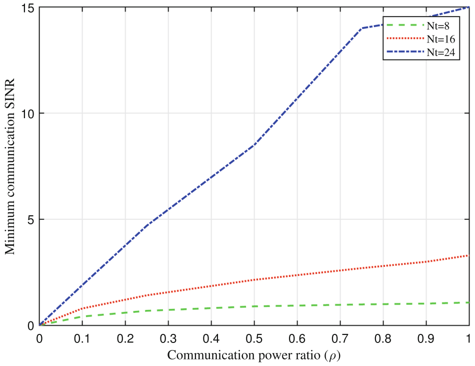

Fig. 2. Effect of different antenna number on JSC algorithm (SINR ρ)

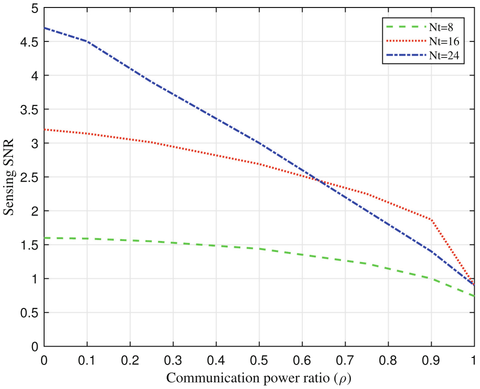

Fig. 3. Effect of different antenna number on JSC algorithm(SNR ρ)

4.1 The Effect of Different Number of Antennas

It can be seen from Fig. 2 and Fig. 3 that when the influence of communication power ratio on minimum communication SINR and sensing SNR is studied, with the constant number of users, the more antennas there are, the larger the minimum communication SINR will be as the communication power ratio increases. In addition, with a higher number of antennas, sensing performance degrades faster as more power is allocated to the communication beam. It can be seen that the more antennas there are, the faster the communication or sensing performance changes when the power distribution between communication and sensing changes. With the increase of the communication power ratio, the communication SINR and sensing SNR curves with different antenna numbers have excellent convergence performance.

In addition, with the increase of the communication power ratio, the power allocated to the communication beam gradually increases, and the power allocated to the sensing beam gradually decreases. Therefore, when the communication power ratio increases, the minimum communication SINR shows an upward trend, while the sensing SNR shows a downward trend. At this time, the communication performance becomes better and better, and the sensing performance gradually deteriorates.

4.2 The Effect of Different Number of Users

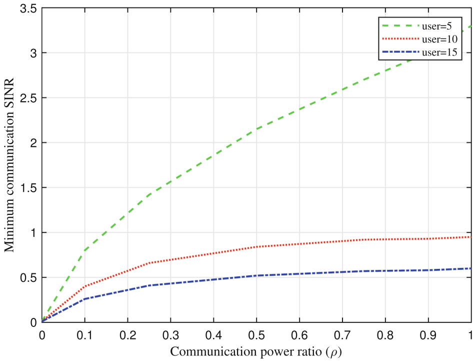

Fig. 4. The influence of different number of users on JSC algorithm (SIN ρ)

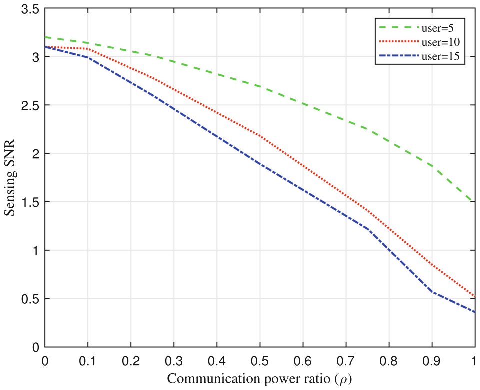

Fig. 5. The influence of different number of users on JSC algorithm (SNR ρ)

As can be seen from the simulation results in Fig. 4 and Fig. 5, when the number of antennas remains unchanged, the smaller the number of users, the larger the minimum communication SINR and sensing SNR will be when the communication power ratio increases. This is because when the number of antennas is fixed, the fewer the number of users means that each user can get more antenna resources, thereby increasing the quality of its received signal. Therefore, the minimum communication SINR will be relatively large, and when the number of users increases, each user will need to share more antenna resources, resulting in a decline in signal quality, the minimum communication SINR will be relatively reduced, and the impact on the sensing SNR is relatively small. With the increase of the communication power ratio, the communication SINR and sensing SNR curves of different users tend to be stable and still have excellent convergence performance.

It can be seen from the above results that the algorithm has good convergence under different number of antennas and different number of users.

5 Conclusion

In this paper, an ISAC beamforming algorithm for joint sensing and communication is designed to solve the problem of sensor blind spot in the network of vehicles. The algorithm has better communication and sensing performance, and has better convergence when the number of antennas and the number of users are different.

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