Research on 5G Internet of Vehicles Facilities Based on Coherent Beamforming

Juan Xu[1], Lan Wu[1], Lei Shi[1](✉), Yi Shi[2], and Wenwen Zhou[1]

[1] School of Computer Science and Information Engineering, HeFei University of Technology, Hefei 230009, China
shilei@hfut.edu.cn

[2] Intelligent Automation Inc., 15400 Calhoun Drive, Rockville, MD 20855, USA

Abstract. As an important application scenario of edge computing, the Internet of Vehicles (IoV) is a special wireless network which needs a serious requirement on communication speed and latency. Nowadays, the 5G wireless networks have been put into commercial use, which makes IoV's higher speed and lower latency requirements possible. However, comparing with 4G base station, the cost of 5G base station is very high, while its cover range is small. These weaknesses make 5G wireless network difficult to be used directly on IoV. Fortunately, Coherent Beamforming (CB) technology makes the long distance transmission possible in 5G wireless network. While as a new technology in communication, few works has been done on considering to use it on IoV. In this paper, we consider to use CB on IoV scenario. We aim to give an optimal scheme for deploying the roadside CB-nodes so that we can transmit data to the edge server with a low cost. We first give the mathematical model and clarify that it is an NP-hard model. Then we design a heuristic algorithm for solving the problem. We call our algorithm as the Iterative Coherent Beamforming Node Design (ICBND) algorithm. Simulation results show that the ICBND algorithm can greatly reduce the cost of communication network infrastructure.

Keywords: Coherent Beamforming · Edge computing · Internet of Vehicles · 5G

1 Introduction

As people's pursuit of comfort and safety keeps improving, the research about Internet of Vehicles (IoV) receives much attention and has been studied more [1–3]. Especially in recent years with the development of artificial intelligence technology, people have paid much attention to automatic driving technology. Autonomous driving technology relies much on the development of the vehicles

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communicating ability with their surroundings. As a hot research field, edge computing, which sinks a large number of complex calculations into the edge server environment, thus makes automatic driving technology possible [4], and plays an important role in autonomous driving [5,6], Internet of things (IoT) [7] and other research fields [8–10]. The basic communication of the edge computing framework is built on the 5G network. 5G has characteristics of high data volume and low latency [11]. In addition to bringing more extreme experience and larger capacity, 5G technology is now widely discussed in smart grids, interconnected vehicles, autonomous driving and surgery [13], and will open the era of the IoV and penetrate into various industries [12]. However, compared with current commercial 4G technology, 5G also have disadvantages. The coverage of 5G base station (BS) is small and the cost is high [14]. Due to the wide range of automobile work scenarios, it is difficult for 5G to directly replace the 4G based vehicle networking system. Fortunately, in recent years, the communication technology based on coherent beamforming (CB) has provided the possibility of large-scale data communication.

CB technique needs multiple nodes work together for increasing the transmission range. When CB technology is used for transmitting, each node will use one omnidirectional antenna. In [15], the authors have proved that the power gain of N senders and M receivers in CB communication can reach to N^2M. Nowadays some studies about CB have been done, but most are focused on power and delay issues. For example, in [16], the authors designed an open-loop CB scheme for MISO communications. In [17], the authors proposed an adaptive beamforming to improve the contrast to noise ratio. In [18], CB was applied to the radar system, so that the MIMO radar can meet the spatial domain transmit beamforming constraints.

To our knowledge, most predecessors use CB technology to study network throughput and power problems. We are the first to explore the application of CB technology in 5G vehicle networking. We try to expand the communication range and reduce the number of base stations so as to reduce the cost without reducing the communication requirements of vehicles. In this paper, we analyze the working model of CB in 5G vehicle network. We place CB-nodes reasonably and effectively on both sides of the road. These CB-nodes can collaborate to help the vehicle transfer data to the edge server. Compared with 5G base station layout, the delay of this method is similar to the layout of 4G base stations, which greatly reduces the cost of infrastructure.

The rest of the article is organized as follows. In Sect. 2, we give the system model and algorithm. The designed model is a NP-hard problem, and it is difficult to find the optimal solution directly. Then we design a heuristic algorithm for Iterative Coherent Beamforming Node Design (ICBND) based on greedy strategy to find the optimal number of nodes in each subpart, and obtain the approximate optimal solution by combining the optimal value of each subpart. In Sect. 3, we give a comparison experiment, and propose a control variable method to compare the simulation results of the two methods. In Sect. 4, we give the conclusion.

2 System Model and Problem Definition

We first describe the system model (see Fig. 1). Consider a part of straight road with the length L. An edge server is located on the road side, near the center point of the road. A number of wireless nodes are placed on both sides of the road for helping communicating. When a vehicle is passing the road, it will communicate with the edge server by the help of these nodes. The vehicle will first broadcast data to its nearby nodes, and then these nodes will collaborate to send data to the edge server by using the CB technique. We call these nodes as CB-nodes. Suppose the vehicle need to transmit D data to the edge server, and suppose it will pass the road by T time. We want to give an optimal scheme for deploying CB-nodes, so that we can use a minimum number of CB-nodes while guaranteeing that the vehicle can finish its transmission job in T time. When different vehicles pass the road, they may have different speed and different transmission requirement. This may lead different optimal solutions. So we suppose we design the optimal solution for the vehicle with the maximum speed (which leads a minimum passing time T) and the maximum transmission requirement (which leads a maximum data D).

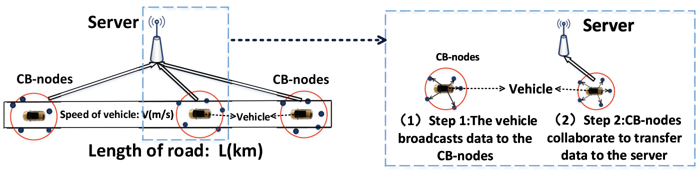

Fig. 1. CB-nodes collaborates with the vehicle to transmit data.

2.1 Network Layer Model and Problem Formulation

Denote s_i as one of the CB-node, denote N as the set of all CB-nodes, i.e., $s_i \in N$, and denote n as the number of N. In the scheduling time T, the whole Data D may be divided into several pieces and several different CB-nodes may collaborate for each transmission. Denote S_j as one group of CB-nodes that collaborate for a transmission, denote M as the set of all CB-node groups, i.e., $S_j \in M$, and denote m as the number of M. Apparently $m \ll 2^n - 1$. Notice that one CB-node s_i may be in different groups. Denote $D(S_j)$ as the data of S_j's transmission, we have

$$D = \sum_{j=1}^{m} D(S_j). \tag{1}$$

One transmission has two stages. First, the vehicle broadcasts data to its nearby CB-nodes. Second, CB-nodes transmit data to the edge server. For the first stage, denote binary variables $x_{s_i}(t)$ and $x_{S_j}(t)$ to indicate if s_i or S_j receives the vehicle's broadcasting data at time t, i.e., if $x_{s_i}(t) = 1$ (or $x_{S_j}(t) = 1$), it means that s_i (or S_j) will receive data at time t. For the second stage, similar to the first stage, we will denote binary variables $y_{s_i}(t)$ and $y_{S_j}(t)$. Then we have

$$x_{s_i}(t) \geq x_{S_j}(t) \text{ and } y_{s_i}(t) \geq y_{S_j}(t) \quad (\forall i, s_i \in S_j, 0 \leq t \leq T), \tag{2}$$

For s_i (or S_j), it can only receives or transmits data at time t, we have

$$x_{s_i}(t) + y_{s_i}(t) \leq 1 \text{ and } x_{S_j}(t) + y_{S_j}(t) \leq 1. \tag{3}$$

Only one group can receive the broadcasting data at time t, and only one group can transmit to the edge server at time t, we have

$$\sum_{S_j \in M} x_{S_j}(t) \leq 1 \text{ and } \sum_{S_j \in M} y_{S_j}(t) \leq 1. \tag{4}$$

Denote P_v as the transmission power of the vehicle, then the vehicle's transmission range can be formulated as $R_v = \sqrt[\lambda]{(P_v/\beta N_0)}$, where N_0 is the noise power, λ is the pass loss index, and β is a constant. We can get similar formulation about a single CB-node's transmission range $R_s = \sqrt[\lambda]{(P_s/\beta N_0)}$, where we suppose all CB-nodes have the same transmission power P_s. Denote $\sigma_{v \to s_i}^{S_j}(t)$ as the signal-to-noise-ratio (SINR) from the vehicle to s_i of the set S_j at time t, denote $d_{v \to s_i}(t)$ as the distance between the vehicle and s_i at time t, we have

$$\sigma_{v \to s_i}^{S_j}(t) = \frac{P_v d_{v \to s_i}^{-\lambda}(t) \cdot x_{S_j}(t)}{N_0} \geq \beta \cdot x_{S_j}(t) \quad (s_i \in S_j, S_j \in M). \tag{5}$$

Denote $\sigma_{S_j \to b}(t)$ as the sum of SINR from all CB-nodes in S_j for sending data to the edge server at time t, and denote $d_{s_i \to b}$ as the distance between s_i and the edge server. Since we use the CB technique for transmissions, which means several CB-nodes will cooperate for transmitting, we have

$$\sigma_{S_j \to b}(t) = \frac{P_s(\sum_{s_i \in S_j} \sqrt{d_{s_i \to b}^{-\lambda}})^2 \cdot y_{S_j}(t)}{N_0} \geq \beta \cdot y_{S_j}(t) \quad (S_j \in M). \tag{6}$$

Denote $r_{v \to s_i}^{S_j}(t)$ as the vehicle's transmitting data rate to s_i of the set S_j at time t, and denote $r_{S_j \to b}(t)$ as the transmitting data rate from the set S_j to the edge server at time t. Denote W as the bandwidth. Since the transmitting data rate should not be larger than the channel capacity, we have

$$r_{v \to s_i}^{S_j}(t) \leq W \log_2(1 + \sigma_{v \to s_i}^{S_j}(t)) \quad (s_i \in S_j, S_j \in M, 0 \leq t \leq T), \tag{7}$$

$$r_{S_j \to b}(t) \leq W \log_2(1 + \sigma_{S_j \to b}(t)) \quad (S_j \in M, 0 \leq t \leq T). \tag{8}$$

Consider the relationship between the transmitting data rate and the transmitting data of a set S_j, and the second step, we have

$$D(S_j) = \int_{t=0}^{T} r_{v\to s_i}^{S_j}(t)dt = \int_{t=0}^{T} r_{S_j\to b}(t)dt \quad (s_i \in S_j, S_j \in M, 0 \leq t \leq T). \quad (9)$$

$$\int_{t=0}^{\eta} r_{v\to s_i}^{S_j}(t)dt \geq \int_{t=0}^{\eta} r_{S_j\to b}(t)dt \quad (s_i \in S_j, S_j \in M, 0 < \eta \leq T). \quad (10)$$

Denote n_{max} as the maximum number of roadside CB-nodes arranged on. Apparent if we deploy enough CB-nodes by the roadside the vehicle will always complete the communication properly. So suppose we first deploy enough CB-nodes by the roadside, then we try to find nodes which are not used in the whole scheduling time as many as possible, we will get the optimal solution. That is, we are trying to find CB-nodes s_i that satisfies $y_{s_i}(t) = 0$ when each vehicle passes through the entire road. We can set a binary variable z_i

$$z_i = \begin{cases} 1 : \exists \quad y_{s_i}(t) = 1, 0 \leq t \leq T \\ 0 : \forall \quad y_{s_i}(t) = 0, 0 \leq t \leq T. \end{cases} \quad (11)$$

Based on the above discussions, we can get the final formula,

$$\begin{array}{ll} \min \sum_{i=1}^{n_{max}} z_i \\ \text{s.t.} \;\; (1), (2) - (11). \end{array} \quad (12)$$

However, notice that in (12), we do not know which specific CB-node in each set S_j, and the number of all sets m may be a very large number. We also notice that $x_{s_i}(t)$, $y_{S_j}(t)$ are continuous variables about time t, which means we have infinite variables. So (12) cannot be solved directly.

2.2 Problem Refinement

In Sect. 2.1, we give the problem formulation. In this sub section, we will give the problem model reformulation. Notice that for (12), we divide the whole data D into many small parts $D(S_j)$, and for each part we use a different CB-node-set S_j for serving it. If we can design an algorithm for establishing S_j, then we may find a way to solve (12). To do that, we need to answer three problems. (i), How many parts we should divided at least for D? (ii), For each S_j, how many nodes should be included in? (iii), Are there any CB-nodes in different S_j?

For the first problem, notice that the vehicle usually travel with a constant speed and we assume that the vehicle has a speed v in time T. We have $v \leq v_{max} = \frac{L}{T}$. Define the amount of data sent by each part as $D(S_j)$. Since the time of each vehicle's transmission is the time when the vehicle passes through the CB-node's transmission range, (i.e, $2R_s$), we should ensure that the vehicle completes the transmission within $\frac{2R_s}{v_{max}}$ time. Assume that the CB-node's transmission range in each segment is not intersected with the other segments, we will equally divide the whole road for $h \geq h_{min} = \frac{L}{2R_s}$ parts at least. In each path part l_j, we will arrange a set S_j for transmitting $D(S_j)$ to the edge server. We also notice that when the vehicle enters a path part, the distance between it and the CB-nodes in this part will not change too much. So we can consider $d_{v \to s_i}(t)$ as a constant d_v, and the data transmission rate $r_{v \to s_i}^{S_j}$ as a constant r_v.

For the second problem, the needed CB-nodes number is decided by the distance between the edge server and each set, and now we have known S_j is arranged for l_j. Denote the distance as $d(S_j)$. Denote the needed number of CB-nodes as $n(S_j)$. We have

$$n(S_j) = \lceil \frac{d(S_j)}{R_s} \rceil. \tag{13}$$

Since we consider the vehicle has a constant speed v, and the road is divided equally, so the vehicle will pass each road path part with a same time slot length. Denote time slot as $t_i (i = 1, 2, ..., h)$. We have $t_1 = t_2 = \cdots = t_h$. Then we have,

$$D(S_j) = \frac{D}{h} = r_v \cdot t_j \leq W \log_2(1 + \sigma_{v \to s_i}^{S_j}(t_j)) \cdot t_j. \tag{14}$$

Based on the first discussion and the second discussion, we can get a feasible solution, only if we put enough CB-nodes in each CB-node-set. The result of the third problem is affected by the length of the segment and the propagation range of the CB-node. We refer to the same CB-node in different set of CB-nodes as a cross-bit CB-node. In the following, we set up the ICBND algorithm. According to the number of segments, we get the minimum number of CB-nodes needed for each segment to work separately, and calculate the number of cross-bit CB-nodes. We remove repeated CB-nodes to obtain the optimal total number of CB-nodes. The specific steps are described in the next sub section.

2.3 Algorithms

For the third problem, we notice the whole road has been divided into $h (h_{min} \leq h \leq h_{max})$ path parts. Since the vehicle has a permanent transmission range R_v, it is easy to find that with the different number of road path parts, several CB-node-sets can be in one vehicle's transmission range (see Fig. 2). In these situations, in order to describe the problem more conveniently, if we put the cross-bit CB-nodes in the common parts, we will save more CB-nodes. Based on these discussions, we try to propose our heuristic algorithm. The main idea of our algorithm is based on iterative steps. We call our algorithm as the Iterative Coherent Beamforming Node Design (ICBND) algorithm. In the following we give the main four steps of the ICBND algorithm.

First, initialization h_{max}, h_{min}, etc. Determine the road is divided into h segment, and calculate the distance from the center of each segment to the edge server. Then, the number of CB-nodes required for each segment individually is calculated according to Eq. (11), and the number of CB-nodes required for each segment is temporarily stored in an array.

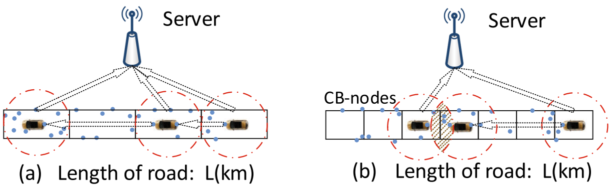

Fig. 2. CB-nodes layout scheme.

Second, input the broadcast range and segment length of the CB-node and calculate the number of cross-bit CB-nodes in each segment.

Third, each segment has at least one receiving CB-node, and other CB-nodes can be placed on the intersection of the two segments.

Fourth, add the minimum number of CB-nodes for each segment.

Algorithm 1. Algorithm for Iterative Coherent Beamforming Node Design

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Require: Initializing h_{min},h_{max}; initial the CB-nodes $sum = 0$;

initial $x = 0$, $j = 1$, $h = h_{min}$;
repeat
  repeat
    Calculate the distance between S_j and the edge server: $d(S_j)$;
    Calculate the number of CB-nodes in the each region: $n(S_j) = \lceil \frac{d(S_j)}{R_s} \rceil$;
    Determine the relation between R_s the value between h_{min} and h_{max} , then calculate that the same CB-node exists in several different sets of CB-nodes;
    Calculate x, $n(S_j) = n(S_j) - x$;
    $sum = sum + n(S_j)$;
  until The vehicle ran the last part of the road, $j = h$;
  get one kind of task assignment scheme
until $h = h_{max}$;
select the best assignment scheme to be the assignment scheme for this time slice;

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3 Simulation

In this section, we will give simulation results. We first give a specific layout scheme for a particular network, and then give the comparison results of more network schemes. We set the straight-line distance between the edge server and the road is $a = 100\,\text{m}$. The noise power N_0 is 10^{-7} W, and the road strength loss factor $\lambda = 3$. The total bandwidth of road strength $W = 3.5\,\text{GHz}$. Denote the vehicle's broadcast range as the CB-node's broadcast range.

3.1 A Special Case with CB-nodes Layout

In this section, under the condition that the road length is $L = 4\,\text{km}$. the transmission power P_s of the CB-node is $0.3\,\text{W}$, and the broadcast radius is

$R_s = 144\,\mathrm{m}$. According to the algorithm 1 execution results, the data with cross-bit CB-nodes from 98 to 173, and the data without cross-bit CB-nodes from 154 to 462. the total number of with cross-bit CB-nodes is always less than the total number of without cross-bit CB-nodes, so the scheme with cross-bit CB-nodes has advantages. According to the data, the total number of optimal CB-nodes is 98. Based on this, we adopt the optimal CB-nodes layout scheme to simulate the layout of real road CB-nodes, as shown in Fig. 3.

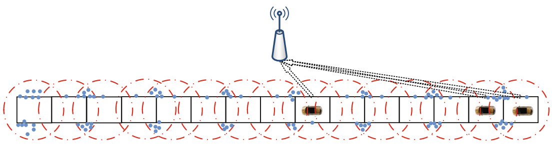

Fig. 3. The optimal CB-nodes layout scheme in a specific scenario.

According to market research, we set the cost of a CB-node at \$15 and the cost of a 5G base station at \$28000. For normal communication, a 5G base station needs to be deployed every 200 m. The data shows that the optimal scheme is 98 CB-nodes and one edge server, and the cost is \$29470. The length of the road is $L = 4\,\mathrm{km}$, so 20 5G base stations are needed and the cost is about \$560000. So, we could save about \$530530 based on our planned layout.

3.2 General Case

In this section, we give more experimental results for different parameter settings. We let L change from 2 km to 8 km, with the step 1 km, and let P_s change from 0.2 W to 0.5 W, with the step 0.1 W. Then we can calculate different R_s as 126 m, 144 m, 159 m and 170 m. Based on these settings, we can get a series of results, as shown in Fig. 4.

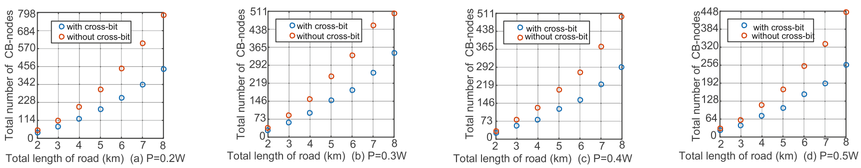

Fig. 4. Different number of CB-nodes needed under different L and P_s.

As shown in Fig. 4, data with cross-bit CB-nodes scheme is always better than data without cross-bit CB-nodes scheme. Then, we compare the scheme with cross-bit CB-nodes scheme with the 5G base station scheme. In detail, as shown in Fig. 4(b), when $P_s = 0.2\,\mathrm{W}$, the optimal number of CB-nodes that needed with the cross-bit scheme in different L are 28, 60, 98, 150, 192, 262 and 342, respectively. The corresponding costs are approximately \$28420, \$28900, \$29470, \$30250, \$30880, \$31930 and \$33130. When L values from 2 km to 8 km, with the step 1 km, the number of 5G base stations from 10 to 40, with the step 5. The corresponding costs from \$280000 to \$1120000, with the step \$140000. Therefore, adopting our method can greatly reduce the cost of infrastructure.

4 Conclusion

In this work, we study the use of coherent beamforming technology on IoV scenario. We build a general model for this problem, with the goal of reducing the communication cost as much as possible while satisfying the transmission conditions. Since the designed model is NP-hard problem, we propose an effective heuristic algorithm ICBND, it using the iterative method to calculate the total number of the least CB-nodes on the whole road. In the simulation experiment, we compared the scheme with cross-bit CB-node, the scheme without cross-bit CB-node and the scheme of 5G base station layout, comparative experiments show that our algorithm has low cost performance.

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