Jointly Optimizing Throughput and Cost of IoV Based on Coherent Beamforming and Successive Interference Cancellation Technology

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Abstract. The high transmission performance of 5G provides the Internet of Vehicles (IoV) more opportunities for doing tasks which need to handle large amount of data within a small time span. However, 5G base station has a small coverage and a high cost which may restrict its development in the IoV. In this paper, we try to give some feasible solution for this problem. We will use two physical layer techniques, the coherent beamforming (CB) technology and the successive interference cancellation (SIC) technology to increase the total amount of data transmitted by vehicles while reducing network infrastructure costs. We first establish the mathematical model and prove it couldn't be solved directly, and then design two algorithms, the Road and CB-nodes Assignment (RCA) algorithm and the Throughput Optimization of Vehicle Scheduling based on SIC (TOVSS) algorithm. Simulation results show that our method has the advantages of cost saving and throughput improvement.

Keywords: Coherent beamforming · Edge computing · Internet of Vehicles · 5G · Successive interference cancellation

1 Introduction

As an important research and industrial field, the Internet of Vehicles (IoV) has been studied for some years [1,2]. However, since people's pursuit to the quality of experience (QoE) grows constantly, the privacy and efficiency of data processing has always been a concern [3–5], among them, the problem of task unloading in Internet of Vehicles has always been concerned [6,7]. Recently, many researchers focus on the edge computing technique on the IoV, which makes lots of complex computing tasks work on the edge servers to makes it possible to improve the

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data throughput [8]. The basic communication of the edge computing framework is built on the 5G network, with the characteristics of high data volume and low latency [9]. However, the base station of 5G has the shortcoming of high cost and small coverage area [10], which may delay the development of the edge computing technique on the IoV.

Fortunately, the coherent beamforming (CB) technology provides us a method to compensate for the 5G's shortcoming. The transmitting node needs to broadcast data to several other idle nodes, which will then help the transmitter's transmitting, thus increasing the transmission distance by increasing the power gain. Many researchers have done their work on CB. In [11], authors developed an improved beamforming scheme which has clutter suppression capability and sensitivity to signal energy. In [12], authors presented a novel space-time waveform design scheme for MIMO radar to meet the beamforming constraints and requirements of waveform orthogonality in time domain. In [13], authors proved that the power gain of N senders and M receivers in coherent beamforming communication can reach N^2M to improve transmission range of the node.

Another useful technology for 5G environment is the successive interference cancellation (SIC). When using the SIC technology, a receiver can receive multiple signals simultaneously from transmitters. The receiver will first decode the strongest signal in the multiple data. After a successful receiving, the strongest signal will be removed from the initial multiple data. The cycle is repeated until all signals are decoded or some signal cannot be decoded. In [14], authors promoted the SIC use in multi-hop wireless network by systematically studying. In [15], authors proposed the use-up-link-capacity iterative (UULC-iterative) algorithm to improve throughput. In [16], authors proposed a new algorithm by combining the SIC technique with the neighbor discovery algorithm to improve the performance of the original neighbor discovery algorithm.

However, no paper considers using SIC and CB to improve the QoE of IoV and makes the use of 5G become reality. In our previous work, we have build a relatively simple model based on CB technology, then optimized the CB-node layout scheme to reduce the cost of network communication [17]. In this paper, we try to study the task unloading problem for multiple vehicles by using CB and SIC under 5G vehicle networking scenario, under the premise of reducing the communication cost while maximizing the unloading data amount.

The paper is organized as the following. In Sect. 2, we analyze the mathematical model of CB and SIC for 5G multi-vehicle network and the mathematical model is reorganized. In Sect. 3, we design two algorithms which we name as RCA and TOVSS. In Sect. 4, we chose two groups of comparative experiments, and obtained the superiority of our algorithms. In Sect. 5, we conclude the whole paper.

2 System Overview

We first describe the system model. Consider a straight multiple-lane road. An edge server is located on the road side and covers a part of the road with length

L. A number of wireless nodes are placed on both sides of the road for helping communicating, vehicles 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 each vehicle needs to upload at least D_{min} data to the edge server. According to our previous research results, in this paper, we want to present an optimal scheduling scheme to maximize the sum of the total data D_{total} transmitted by all vehicles while reduce the cost of network transmission infrastructure.

2.1 System Model and Problem Formulation

Denote s_i as one of the CB-node. Denote N as the set of all CB-nodes, i.e., $s_i \in N$. Denote n as the number of N. Denote b as the edge server. Denote S_j as the set of fixed CB-nodes required for each vehicle to transmit data. Denote M as the set of all CB-node groups, i.e., $S_j \in M$. Denote m as the number of M. Since the CB-node is a low cost device, we suppose there are enough CB-nodes in each set. **Apparently** $m \ll 2^n - 1$. Denote c_l as one of vehicles. Denote C as the set of all vehicles on that section of the road in time T, i.e., $c_l \in C$. Denote q as the number of C. Suppose the whole schedule time T is divided into h time slots equally, and denote time slot as $t_k(i = 1 \dots h)$. We have $t_1 = \cdots = t_h$. Denote D_l as the amount of data for vehicle c_l's transmitting. Denote D_l^j as c_l's transmitting data to the set S_j, then we have

$$D_{min}^l \leq D_l = \sum_{j=1}^{m} D_l^j. \tag{1}$$

One transmission data has two stages. In the first stage, the vehicle broadcasts data to its nearby CB-nodes. In the second stage, CB-nodes transmit data to the edge server by using CB technique. We use $x_{c_l \to S_j}(t_k)$, $x_{S_j \to b}(t_k)$ to indicate the transmission cases of a CB-node or a set at time t_k, i.e., if $x_{c_l \to S_j}(t_k) = 1$ (or $x_{S_j \to b}(t_k) = 1$), it means that S_j (or b) will receive data at time t.

For a set S_j, it cannot transmit or receive simultaneously. We have

$$x_{c_l \to S_j}(t_k) + x_{S_j \to b}(t_k) \leq 1 \quad (\forall j, l, k, S_j \in M, c_l \in C, t_k \in T). \tag{2}$$

When using SIC technology, multiple sets of CB-node can transmit data to the edge server at the same time. Suppose there are at most m CB-node sets which can transmit simultaneously, we have

$$\sum_{S_j \in M} x_{S_j \to b}(t_k) \leq m. \tag{3}$$

When using the SIC technology, for the first step, the signal-to-noise-ratio $SINR_{c_l \to s_i}(t_k)$ from c_l to the CB-node s_i at time t_k can be expressed as

$$SINR_{c_l \to s_i}(t_k) = \frac{(d_{c_l \to s_i}(t_k))^{-\lambda} P_v \cdot x_{c_l \to S_j}(t_k)}{\sum\limits_{c_g \in C, c_l \neq c_g} (d_{c_g \to s_i(t_k)})^{-\lambda} P_v + N_0} \geq \beta \cdot x_{c_l \to S_j}(t_k), \tag{4}$$

where P_v is the transmission power of each vehicle, N_0 is the noise power, λ is the pass loss index, β is a constant, and $d_{c_l \to s_i}(t_k)$ is the distance between the vehicle c_l and the CB-node s_i at time t_k.

For the second step, denote $SINR_{S_j \to b}(t_k)$ as the sum of SINR from all CB-nodes in the group S_j sending data to the edge server collaboratively at time t_k, we have

$$SINR_{S_j \to b}(t_k) = \frac{(\sum\limits_{s_i \in S_j} \sqrt{d_{s_i \to b}^{-\lambda}})^2 P_s \cdot x_{S_j \to b}(t_k)}{\sum\limits_{S_l \in G}^{s_l \neq s_i} (\sum\limits_{s_l \in S_l} \sqrt{d_{s_l \to b}^{-\lambda}})^2 P_s \cdot x_{S_l \to b}(t_k) + N_0} \geq \beta \cdot x_{S_j \to b}(t_k), \quad (5)$$

where $d_{s_i \to b}$ is the distance between s_i and the edge server, G is the set for all CB-node sets which satisfy the condition $(\sum\limits_{s_l \in S_l} \sqrt{d_{s_l \to b}^{-\lambda}})^2 P_s < (\sum\limits_{s_i \in S_j} \sqrt{d_{s_i \to b}^{-\lambda}})^2 P_s$, and P_s is the transmission power for each CB-node (suppose all CB-nodes have the same power).

Then we can represent D_l^j and D_l in (1) to (6) and (7). Denote W as the bandwidth, we have,

$$D_l^j = \sum_{k=1}^{h} W \log_2(1 + SINR_{c_l \to S_j}(t_k)) \cdot x_{c_l \to S_j}(t_k), \quad (6)$$

$$D_l = \sum_{j=1}^{m} D_l^j = \sum_{j=1}^{m} \sum_{k=1}^{h} W \log_2(1 + SINR_{c_l \to S_j}(t_k)) \cdot x_{c_l \to S_j}(t_k). \quad (7)$$

Denote D_j as the amount of data received over the entire time period T. Since the amount of data transmitted by the vehicle to the set should be equal to the amount of data transmitted by the set to the edge server, we have

$$D_j = \sum_{k=1}^{h} W \log_2(1 + SINR_{S_j \to b}(t_k)) \cdot x_{S_j \to b}(t_k) \quad (\forall j, S_j \in M) \quad (8)$$

Denote D_{total} as the total of data transmitted by all vehicles pass through the whole road at time T, we have

$$D_{total} = \sum_{l=1}^{q} D_l = \sum_{l=1}^{q} \sum_{j=1}^{m} \sum_{k=1}^{h} W \log_2(1 + SINR_{c_l \to S_j}(t_k)) \cdot x_{c_l \to S_j}(t_k). \quad (9)$$

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

$$\begin{aligned} &\max D_{total} \\ &\text{s.t.} \quad (1), (2) - (9). \end{aligned} \quad (10)$$

Notice that in (10), we don't know how many S_j and the number of m may be a very large number. We also notice that we have variable $x_{c_l \to S_j}(t_k)$ in the numerator and the denominator about time t_k. So (10) cannot be solved directly.

2.2 Problem Refinement

In this section, we reformulate the problem of the previous section. Notice that we have two main problems to design the algorithm. First, how to determine the exact number of CB-node sets and the exact number of CB-nodes in each CB-node set. Second, how to determine which time slots for vehicles or CB-node sets communication by calculating the variables of $x_{c_l \to S_j}(t_k)$ and $x_{S_j \to b}(t_k)$.

We now discuss the first problem. Since vehicles usually travel with constant speeds on roads and we assume that the vehicle has a speed v_l in time T. We have $v_l \geq v_{min} = L/T$. We should ensure that each vehicle complete the communication within $\frac{2R_s}{v_{min}}$ time. Assume that the communication range of the CB-nodes in each segment is not intersected with the other segments, we can find that we should at least divide the whole road equally into $h(\geq h_{min} = \frac{L}{2R_s})$ parts. In each path part, denote the length as $l_j (j = 1, 2, ..., h)$, and we will arrange a set S_j for each vehicle transmitting D_l^j data to the edge server. We also notice that when a vehicle entering a path part, the $d_{c_l \to s_i}(t_k)$ in this part will not change too much. So we consider $d_{c_l \to s_i}(t_k)$ as a constant d_{c_l} approximately, and the distance between S_j and the edge server as d_j. We have the following lemmas.

Lemma 1. *If S_j is transmitting data ($x_{S_j \to b}(t_k) = 1$) to the edge server in time t_k, then we have: If $[\beta(n_l^2 \cdot d_l^{-\lambda} + \frac{N_0}{P_s})]^{-\frac{1}{\lambda}} \leq d_j \leq (\frac{n_l^2 \cdot d_l^{-\lambda}}{\beta} - \frac{N_0}{P_s})^{-\frac{1}{\lambda}}$, then S_l cannot transmits data to edge server during time t_k ($x_{S_j \to b}(t_k) = 1$), else the remaining S_l may transmit data to the edge server in time t_k. ($n_l^2 \cdot d_l$) represents the channel gain, d_j represents the distance between the S_j and the edge server, β is a constant, P_s is the CB-node transmission power, λ is the pass loss index [18].*

Lemma 1 has been proved in [18]. According to Lemma 1, we can get $l_j = (\frac{n_j^2 \cdot d_j^{-\lambda}}{\beta} - \frac{N_0}{P_s})^{-\frac{1}{\lambda}} - [\beta(n_j^2 \cdot d_j^{-\lambda} + \frac{N_0}{P_s})]^{-\frac{1}{\lambda}} + \delta$, where δ is a very small number and $x_{S_j \to b}(t_k) = 1$. So, $L = \sum_{j=1}^{h} l_j$.

Denote $(n_j)_{min}$ as the least number of CB-nodes that needed. Denote n_j as the actual number of CB-nodes contained in set, i.e., $n_j \geq (n_j)_{min}$. We have

$$(n_j)_{min} = \lceil \frac{d_j}{R_s} \rceil. \tag{11}$$

Lemma 2. *If the road is divide into h segments, the edge server can receive data simultaneously at most from h CB-node sets when using SIC technology. We can get the number of CB-nodes n_j in each segment l_j through $n_j = \sqrt{\frac{\beta \cdot (\sum_{S_l \in G}^{s_l \neq s_i} n_l^2 d_l^{-\lambda} P_s + N_0)}{P_s \cdot d_j^{-\lambda}}}$. (For space reasons, the proof of Lemma 2 is omitted here.)*

In Lemma 2, n_l, d_l and d_j are unknown, but we know $d_h = \frac{L}{2}$ and $d_j = d_l - l_j$, so that we can get n_h, then we can obtain n_{h-1} and d_{n-1}, so we have

$$n_h = \sqrt{\frac{\beta \cdot N_0}{P_s \cdot d_h^{-\lambda}}}, \ldots, n_1 = \sqrt{\frac{\beta \cdot (\sum_{S_l=S_2}^{S_h} n_l^2 d_l^{-\lambda} P_s + N_0)}{P_s \cdot d_1^{-\lambda}}}. \tag{12}$$

Base on Lemma 1 and Lemma 2, we design the Road and CB-nodes Assignment Algorithm (RCA) for deciding for the number of CB-node sets and the number of CB-nodes in each set.

The second problem is calculating variables $x_{c_l \to S_j}(t_k)$ and $x_{S_j \to b}(t_k)$ in formula (10). $x_{c_l \to S_j}(t_k)$ is about the interference between vehicles and CB-node sets and the data that a particular vehicle transmits to the set S_j. $x_{S_j \to b}(t_k)$ depends on the data received by the edge server and the interference decomposition between the data. We design the Algorithm for Throughput Optimization of Vehicle Scheduling based on SIC (TOVSS) for solving them.

3 Algorithms

In this section, we will introduce algorithms. We will first introduce the RCA algorithm for dividing the road and arranging CB-nodes, and then introduce the TOVSS algorithm for distributing the vehicle's data and get optimal results.

The fist algorithms is RCA algorithm. From Lemma 1 and Lemma 2, we solve the problem of road segmentation and the number of CB-nodes and sets, and can directly get the RCA algorithm, the main steps of the TOVSS algorithm are shown as follows.

Step 1: Initializing l_0, d_0, n_0; initial $j = 1$.

Step 2: Calculate distance between the CB-node set and edge server: $d_j = d_{j-1} - l_j$, and $l_j = (\frac{n_{j-1}^2 \cdot d_{j-1}^{-\lambda}}{\beta} - \frac{N_0}{P_s})^{-\frac{1}{\lambda}} - [\beta(n_{j-1}^2 \cdot d_{j-1}^{-\lambda} + \frac{N_0}{P_s})]^{-\frac{1}{\lambda}} + \delta$.

Step 3: We set $f = \sum_{S_l \in G}^{s_l \neq s_i} n_l^2 d_l^{-\lambda} P_s$, then we can get $n_j = \sqrt{\frac{\beta \cdot (f \cdot p + N_0)}{P_s \cdot d_j^{-\lambda}}}$.

Step 4: Output and save a series of data about l_j and n_j.

The second algorithms is TOVSS algorithm. Since the two variables $x_{c_l \to S_j}(t_k)$ and $x_{S_j \to b}(t_k)$ in formula (10) are affected by the time slice, the result of the later time slice will be affected by the result of the previous time slice, we need to design an algorithm to solve it. The main steps of the TOVSS algorithm are shown as follows.

Step 1: Input the data obtained by RCA, L, l_j, d_j, h; Initialize D_l.

Step 2: If several vehicles are in the same segment i, we will select one of them to broadcast data. According to the v_l, the D_l, and the road conditions, the most appropriate vehicle is selected for data transmission.

Step 3: First, we judge whether the i is idle. If no vehicle occupies it, we according to S_j send data to the edge server of interference situations and task emergencies to determine whether it sends the cached data or it receives the data in the current time slice. If no vehicle occupies it to broadcast data and it hasn't cached data, it will receive broadcast data from vehicle. If the i has been occupied by the vehicle, we do not operate. When the segment i is decided to receive broadcast data of vehicle, the vehicle selected in the previous step can broadcast data to S_j in the current segment i, i.e., $(x_{c_l \to S_j}(t_k) == 1)$.

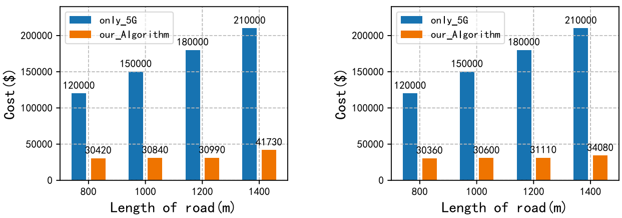
Step 4: Record the amount of data transmitted by each vehicle, sum it up.

4 Simulation

In this section, we give simulation results. Firstly, we use the RCA algorithm to calculate the number of CB-nodes and the cost under different length of road, and compare it with the cost of the layout scheme of 5G base stations. Then, we use the TOVSS algorithm to calculate results compare them with the scheme only CB technology and the scheme only SIC technology (it covered by 4G base station which transmission rate is 75 Mbps). The straight-line distance between the edge server and the road is $a = 100$ m. The noise power N_0 is 10^{-9} W. The road strength loss factor $\lambda = 3$ and bandwidth $W = 1$ GHz.

4.1 Compare the Cost of Network Infrastructure

In this section, we let L to 800 m, 1000 m, 1200 m 1400 m. The transmission range of 5G base station is 200 m, so if we don't use the CB technique, we may need the number of 5G base stations change from 4 to 7. We let P_s as 0.3 W and 0.4 W. We set the cost of a CB-node at \$15 and a 5G base station at \$30000. According to our algorithms, we can get the total number of CB-nodes and the cost of our scheme is shown in Fig. 1. The blue one represents the cost of the 5G base station layout scheme and the orange one represents using our algorithm.

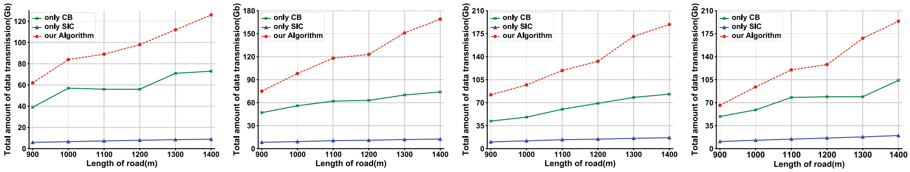


(a) P = 0.3W (b) P = 0.4W

Fig. 1. The cost of infrastructure under different road lengths (Color figure online)

4.2 Comparison of Data Throughput

In this section, we let L change from 900 m to 1400 m, with the step 100 m, and let q to 2, 4, 6, 8, and let $R_s = 144$ m. Based on these settings, we can obtained a series of results. In Fig. 2, the red lines represent D_{total} obtained by our algorithm, and the green ones represent D_{total} obtained by the scheme of only CB technology, the blue ones represent D_{total} obtained by the scheme of only SIC technology and covered by 4G base station. We can see that D_{total} obtained by our algorithm is always the largest, therefore, we can intuitively conclude that our algorithm has the advantage of improving data throughput.



(a) q = 2 (b) q = 4 (c) q = 6 (d) q = 8

Fig. 2. Data throughput with different number of vehicles (q) (Color figure online)

5 Conclusion

In this work, we combine CB and SIC technology for increasing vehicles throughput while reducing the cost of network infrastructure. To address this problem, we develop a general model which cannot be solved directly. Then we propose two algorithms, the RCA algorithm and the TOVSS algorithm. In simulation, we compare our scheme with schemes of only CB and only SIC, and experimental results show that our scheme can save cost and improve throughput respectively.

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