

## Research Article

# Optimize the Communication Cost of 5G Internet of Vehicles through Coherent Beamforming Technology

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Edge computing, which sinks a large number of complex calculations into edge servers, can effectively meet the requirement of low latency and bandwidth efficiency and can be conducive to the development of the Internet of Vehicles (IoV). However, a large number of edge servers mean a big cost, especially for the 5G scenario in IoV, because of the small coverage of 5G base stations. Fortunately, coherent beamforming (CB) technology enables fast and long-distance transmission, which gives us a possibility to reduce the number of 5G base stations without losing the whole network performance. In this paper, we try to adopt the CB technology on the IoV 5G scenario. We suppose we can arrange roadside nodes for helping transferring tasks of vehicles to the base station based on the CB technology. We first give the mathematical model and prove that it is a NP-hard model that cannot be solved directly. Therefore, we design a heuristic algorithm for an Iterative Coherent Beamforming Node Design (ICBND) algorithm to obtain the approximate optimal solution. Simulation results show that this algorithm can greatly reduce the cost of communication network infrastructure.

## 1. Introduction

The concept of Internet of Vehicles (IoV) has been proposed and studied for many years. However, with the continuous improvement of people's pursuit of comfort and safety, Internet of Vehicles (IoV) has been paid more and more attention and research [1–3]. Especially in recent years, automatic driving technology has been of great concern and widely studied with the development of artificial intelligence technology [4]. Autonomous driving technology must rely on the full development of the vehicles' ability to perceive the surrounding environment and communicate. Edge computing is a hot research field in recent years, which sinks a large number of complex calculations into the edge server environment to reduce cloud burden and delay [5], thus making autonomous driving technology possible [6]. Edge computing has played an important role in autonomous driving [7–9], Internet of Things (IoT) [10, 11], data privacy [12, 13], and other research fields [14, 15].

The basic communication of the edge computing framework is built on the 5G network. The 5G network has the characteristics of high data volume and low latency, which is also a key factor to ensure the widespread application of autonomous driving technology in the future [16]. In addition to bringing more extreme experience and larger capacity, 5G will also open the era of the Internet of Things (IoT) and penetrate into various industries [17, 18]. Moreover, 5G is being applied in more and more fields, such as Internet of Things, smart city, traffic driving, and surgery [19]. However, compared with current commercial 4G networks, 5G networks also have disadvantages. The coverage of 5G base stations (BS) is small and the cost is high [20, 21]. Due to the wide range of an automobile's work scenarios and strict requirements on delay, it is difficult for a 5G network to directly replace the current commercial 4G based on vehicle networking systems.

Fortunately, in recent years, the communication technology based on beamforming has provided the possibility of large-scale data communication under the 5G network.

Beamforming is a combination of antenna technology and digital signal processing technology, which is used to transmit or receive directional signals. There are many branches of beamforming, and we will briefly introduce cooperative beamforming and coherent beamforming. Collaborative beamforming technology is a part of collaborative communication science [22, 23]. In collaborative beamforming, nodes are not uniformly distributed and, through calculating the number of optimal array nodes and selecting the optimal array node to establish a virtual antenna array, obtain a high gain beam for transmission and reduce the energy consumption and communication delay of nodes [24]. Even if the destination node is not within the transmission range of the transmission node, as long as there are enough idle nodes around the transmission node, collaborative beamforming can effectively improve the transmission range of a single node [25]. It changes the status quo of long-distance multi-hop wireless transmission, and this technology also improves the reliability and security of data transmission.

In this paper, we use coherent beamforming (see Figure 1; the red node is the transmitting node and the green node is the receiving node). Different from collaborative beamforming technology, CB (coherent beamforming) technology does not have strict requirements on node position and does not generate a high directional beam, and its transmission range is approximately a regular circle. CB technology greatly improves the transmission range of nodes through the cooperation of multiple nodes. When CB technology is used to transmit data, each node uses only one omnidirectional antenna. The transmitting node needs multiple other nodes to help its transmission, thereby improving the transmission distance by increasing the power gain. We aim to use coherent beamforming 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 on the 5G IoV scenario. The main contributions are summarized as follows:

- (1) We use the coherent beamforming technology to reduce the cost of network communication in the scenario of 5G Internet of Vehicles. CB-nodes should be arranged on both sides of the road to assist the vehicle to transmit data to the base station, thus saving the huge cost brought by the arrangement of multiple 5G base stations
- (2) We use CB technology to optimize the cost of communication infrastructure in the Internet of Vehicles scenario and set up a mathematical model; this model is a NP-hard problem, and it is difficult to find the optimal solution directly. For this reason, we design a heuristic algorithm for the Iterative Coherent Beamforming Node Design (ICBND) based on the greedy strategy to find the optimal number of CB-nodes in each subpart and obtain the approximate optimal solution by combining the optimal value of each subpart
- (3) We adopt the layout plan without cross-bit CB-nodes and the 5G base station as a comparative experiment, and we evaluate our algorithm through extensive

simulations. Simulation results demonstrate that the algorithm can achieve superior performance

The rest of the article is organized as follows. Section 2 discusses the related work. Section 3 gives the system model and the problem setting of the total node arrangement on a road and presents an Iterative Coherent Beamforming Node Design algorithm. In Section 4, two control variable methods are proposed and numerical results are given. Section 5 gives the conclusion.

## 2. Related Work

Internet of Vehicles is the development direction of intelligent transportation systems, which is of great significance for solving urban traffic problems. In recent years, the research on Internet of Vehicles has become increasingly hot, focusing on route selection, task transfer, unloading, and so on. In [26], in this paper, they propose a learning method for predicting quality of service (QoS), which achieves an automatic balance between exploration and utilization through automatic adjustment of super parameters based on maximum entropy enhanced learning. In [27], they proposed a multicast data transmission scheme with random delay and minimum cost constraints to optimize congestion of bottleneck vehicle node problem. In [28], the authors combined the vehicle position probability matrix, the vehicle position correlation matrix, and the recessive factor to study the potential function of the influence of the vehicle position; proposed a routing algorithm analysis based on the vehicle position (RAVP); and obtained more accurate vehicle trajectory prediction. In [29], aiming at the security problem of intelligent terminals in IoV, the authors propose two kinds of multimodal implicit authentication protocols based on intelligent terminal privacy protection. The security of the protocol is compared with other related protocols in terms of computing and communication overhead. The results show that the protocol has better security and efficiency. In [30], they propose a two-layer (sensing layer and data processing layer) sensing scheme to optimize link utilization rate and reduce resource consumption in high-speed mobile network IoV. In [31], the authors study the vehicle content cache decision method based on vehicle-to-vehicle collaboration in order to minimize the delay of vehicle content acquisition. In this paper, they propose an on-board content cache algorithm with perceptive delay to optimize the content cache obtained by the vehicle and to optimize the precache decision.

With the in-depth development of 5G, there are more and more articles on the combination of Internet of Vehicles and 5G. 5G has the characteristics of low latency and high data volume and has penetrated into various industries. In [32], the authors analyze and combine blockchain and SDN to effectively operate in the scenario of 5G and fog computing. This paper proposes a trust-based model for controlling network malicious behavior, which helps to relieve the pressure of the controller due to the ubiquitous processing. In [33], in order to solve the problem for distinguishing unloading targets of connected vehicle (IoCV) computing tasks, the

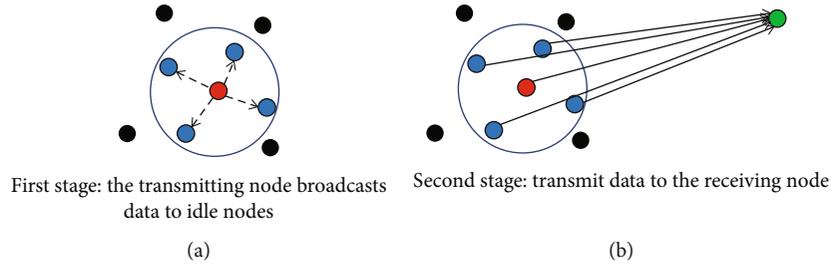


FIGURE 1: Two stages of data transmission in collaborative beamforming technology.

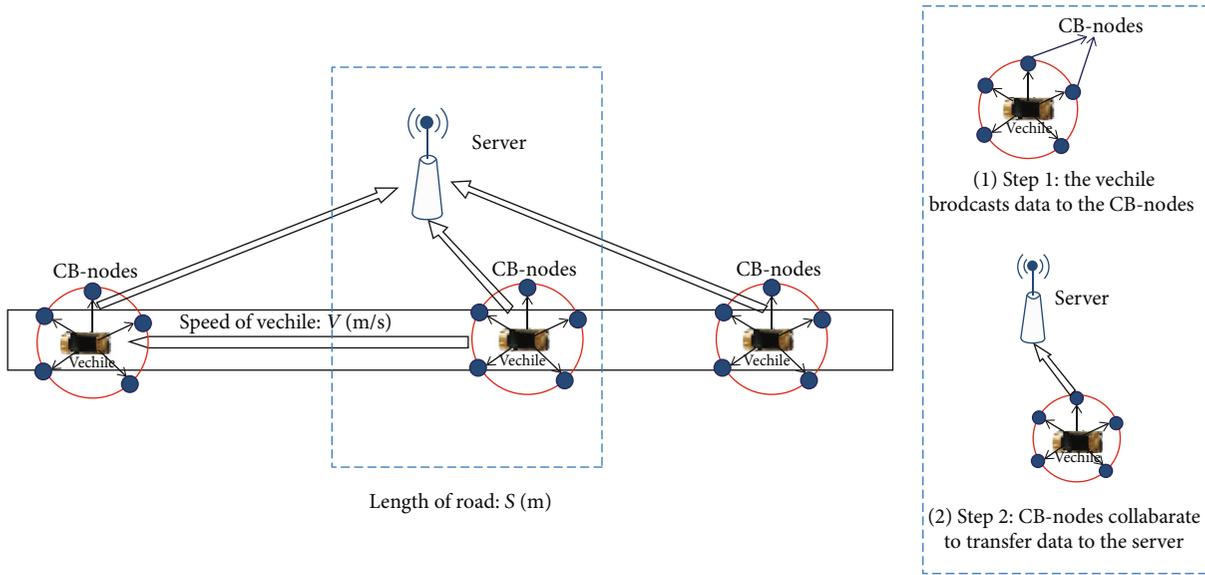


FIGURE 2: CB-nodes collaborate with the vehicle to transmit data.

authors design an adaptive calculating unloading method in 5G IoCV to optimize the unloading delays of tasks and the resource utilization of the edge system. In [34], the authors establish a novel architecture combining satellite networks, vehicle internet, and 5G cloud, which supports seamless and resource management effectively. With the rapid development of the 5G network, opportunities have been brought to the development of the Internet of Vehicles under the scenario of edge computing. In the edge computing IoV system supported by 5G, highly dense 5G base stations can provide rapidity and real-time calculation but, at the same time, increase the cost of network infrastructure [35]. Fortunately, beamforming can alleviate this problem, which improves the receiving power, expands the transmission range, and has low cost. There are several techniques for beamforming. In this paper, we will use coherent beamforming.

Coherent communications were studied mainly for applications in sensor networks or gain of transmitted power. In [36], the authors proved that the power gain of  $N$  senders and  $M$  receivers in coherent beamforming communication can reach  $N^2M$ , and the power and SIR gains obtained are higher than point-to-point transmission; thus, the transmission range of the node is greatly improved. In [37], they designed an open-loop coherent beamforming scheme for

MISO communications and analyzed the basic parameters and common parameters encountered in most open-loop coherent distributed array implementations. In [38], this paper proposed two plans of beamforming to improve the contrast-to-noise ratio; they are the fast minimum variance (FMV) and the fast coherent time delay and correlated pixel-based (FCCP) beamforming. In [39], the authors apply the coherent beamforming technique to MISO to achieve a similar range to minimize transmission power. In [40], an innovative spatiotemporal MIMO radar waveform design method is proposed, and coherent beamforming is applied to the radar system, so that the MIMO radar can meet the spatial domain transmit beamforming constraints and the time domain waveform orthogonality requirements. In [41], this article introduced a technique that can transmit beamforming signals from a node in a distributed radio network to a distant target node through a frequency selective channel to avoid the need for explicit channel status feedback from the destination and solved the problem of the variability of the irreversible effects caused by electronic interference. In [42], they developed the optimal adaptive transmission strategy and the optimal distributed beamforming and resource allocation strategy, and the numerical results proved the superiority of these strategies.

TABLE 1: Notations.

Notation	Description
$s_i$	One of the CB-nodes
$S_j$	One group of CB-nodes that collaborate for a transmission
$R_v$	The radius of the vehicle broadcast
$R_s$	The radius of the CB-node broadcast
$r_{v \rightarrow s_i}^{S_j}(t)$	The vehicle's transmitting data rate to $s_i$ for the set $S_j$ at time $t$
$r_{S_j \rightarrow b}(t)$	The transmitting data rate from the set $S_j$ to the edge server at time $t$
$v(t)$	The speed of the vehicle at time $t$
$d_{v \rightarrow s_i}(t)$	The distance between the vehicle and $s_i$ at time $t$
$d_{s_i \rightarrow b}$	The distance between $s_i$ and the edge server
$n(t)$	The number of CB-nodes that is needed in transmission at time $t$
$\sigma_{v \rightarrow s_i}^{S_j}(t)$	The signal-to-noise ratio (SINR) from the vehicle to $s_i$ for the set $S_j$ at time $t$
$\sigma_{S_j \rightarrow b}(t)$	The sum of SINR from all $s_i$ in $S_j$ to send data to the edge server at time $t$
$\lambda$	The pass loss index
$P_s$	Transmitting power of CB-node sending data to edge server
$P_v$	The power of the vehicle broadcasting data to the roadside CB-node
$W$	Bandwidth
$N_0$	White Gaussian noise power
$D$	The amount of data to be unloaded when the vehicle passes through this section of road

To our knowledge, most predecessors use CB technology to study network throughput and power problems. This is the first time that we try to use coherent beamforming technology to build a communication scheme for the Internet of Vehicles (IoV) under the 5G network. 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. This paper analyzes the working model of coherent beamforming in a 5G vehicle network. We place coherent beamforming nodes reasonably and effectively on both sides of the road. By using coherent beamforming, these CB-nodes can collaborate to help the vehicle transfer data to the edge server. Compared with a 5G base station (BS) layout, the delay of this method is similar to that of the 5G base station layout, which greatly reduces the cost of infrastructure. Then, firstly, we design this problem as a mathematical model and reorganize the mathematical model. Secondly, we design an algorithm that is an Iterative Coherent Beamforming Node Design to solve the approximate optimal solution. Finally, we select two groups of comparative experiments and obtain that our algorithm is superior through the results of multiple experimental data.

### 3. System Model and Problem Definition

We first describe the system model (see Figure 2). Consider a part of a 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 communication. We consider when a vehi-

cle is passing the road; it will communicate with the edge server with 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 coherent beamforming technique. We call these nodes as CB-nodes. Suppose the vehicle needs to transmit  $D$  data to the edge server, and suppose the vehicle will pass the road by  $T$  time. We want to give an optimal scheme for deploying the 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. Notice that when different vehicles pass the road, they may have different speeds and different transmission requirements. This may lead to 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  $D$ ). If the solution can meet this situation, then vehicles with any speed and transmission requirement can finish their jobs in this road. Table 1 summarizes the key parameter symbols in our article.

*3.1. Network Layer Model and Problem Formulation.* Denote  $s_i$  as one of the CB-nodes; 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 be transmitted for several times, and several different CB-nodes may collaborate for each transmission. Denote  $S_j$  as one group of CB-nodes that collaborates 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. Denoting  $D(S_j)$  as the data of  $S_j$ 's transmission, we have

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

One transmission has two stages. First, the vehicle broadcasts data to its nearby CB-nodes. Second, CB-nodes transmit data to the edge server by using a coherent beamforming technique. We use  $x_{s_i}(t)$ ,  $y_{s_i}(t)$ ,  $x_{S_j}(t)$ , and  $y_{S_j}(t)$  to indicate the transmission cases of a CB-node or a set at time  $t$ ; we have

$$\begin{aligned} x_{s_i}(t) &= \begin{cases} 1, & s_i \text{ receives the vehicle's broadcasting data at time } t, \\ 0, & \text{otherwise,} \end{cases} \\ x_{S_j}(t) &= \begin{cases} 1, & S_j \text{ receives the vehicle's broadcasting data at time } t, \\ 0, & \text{otherwise,} \end{cases} \\ y_{s_i}(t) &= \begin{cases} 1, & s_i \text{ transmits data by CB technique at time } t, \\ 0, & \text{otherwise,} \end{cases} \\ y_{S_j}(t) &= \begin{cases} 1, & S_j \text{ transmits data by CB technique at time } t, \\ 0, & \text{otherwise.} \end{cases} \end{aligned} \quad (2)$$

For a set  $S_j$ , when it transmits or receives, all CB-nodes in  $S_j$  should be transmitted or received, respectively. We have

$$\begin{aligned} x_{s_i}(t) &\geq x_{S_j}(t) \quad (\forall i, s_i \in S_j, 0 \leq t \leq T), \\ y_{s_i}(t) &\geq y_{S_j}(t) \quad (\forall i, s_i \in S_j, 0 \leq t \leq T). \end{aligned} \quad (3)$$

For a CB-node  $s_i$  or a group  $S_j$ , it can only receive or transmit data at time  $t$ ; we have

$$\begin{aligned} x_{s_i}(t) + y_{s_i}(t) &\leq 1, \\ x_{S_j}(t) + y_{S_j}(t) &\leq 1. \end{aligned} \quad (4)$$

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

$$\sum_{S_j \in M} x_{S_j}(t) \leq 1, \quad (5)$$

$$\sum_{S_j \in M} y_{S_j}(t) \leq 1. \quad (6)$$

Denote  $P_v$  as the transmission power of the vehicle; then, the vehicle's transmission range can be formulated as  $R_v = \sqrt[3]{P_v / \beta N_0}$ , where  $N_0$  is the noise power,  $\lambda$  is the pass loss index, and  $\beta$  is a constant. We can get a similar formulation about a single CB-node's transmission range  $R_s = \sqrt[3]{P_s / \beta N_0}$ ,

where we suppose all CB-nodes have the same transmission power  $P_s$ . Denoting  $\sigma_{v \rightarrow s_i}^{S_j}(t)$  as the signal-to-noise ratio (SINR) from the vehicle to  $s_i$  of the set  $S_j$  at time  $t$  and denoting  $d_{v \rightarrow s_i}(t)$  as the distance between the vehicle and  $s_i$  at time  $t$ , we have

$$\sigma_{v \rightarrow s_i}^{S_j}(t) = \frac{P_v d_{v \rightarrow s_i}^{-\lambda}(t) \cdot x_{S_j}(t)}{N_0} \geq \beta \cdot x_{S_j}(t) \quad (s_i \in S_j, S_j \in M). \quad (7)$$

Denote  $\sigma_{S_j \rightarrow b}(t)$  as the sum of SINR from all CB-nodes in the group  $S_j$  to send data to the edge server collaboratively at time  $t$ , and denote  $d_{s_i \rightarrow b}$  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

$$\sigma_{S_j \rightarrow b}(t) = \frac{P_s \left( \sum_{s_i \in S_j} \sqrt{d_{s_i \rightarrow b}^{-\lambda}} \right)^2 \cdot y_{S_j}(t)}{N_0} \geq \beta \cdot y_{S_j}(t) \quad (S_j \in M). \quad (8)$$

Denote  $r_{v \rightarrow s_i}^{S_j}(t)$  as the vehicle's transmitting data rate to  $s_i$  of the set  $S_j$  at time  $t$ , and denote  $r_{S_j \rightarrow b}(t)$  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

$$\begin{aligned} r_{v \rightarrow s_i}^{S_j}(t) &\leq W \log_2 \left( 1 + \sigma_{v \rightarrow s_i}^{S_j}(t) \right) \quad (s_i \in S_j, S_j \in M, 0 \leq t \leq T), \\ r_{S_j \rightarrow b}(t) &\leq W \log_2 \left( 1 + \sigma_{S_j \rightarrow b}(t) \right) \quad (S_j \in M, 0 \leq t \leq T). \end{aligned} \quad (9)$$

And considering the relationship between the transmitting data rate and the transmitting data of a set  $S_j$ , we have

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

And the second step should be started after finishing the first step. We have

$$\int_{t=0}^{\eta} r_{v \rightarrow s_i}^{S_j}(t) dt \geq \int_{t=0}^{\eta} r_{S_j \rightarrow b}(t) dt \quad (s_i \in S_j, S_j \in M, 0 < \eta \leq T). \quad (11)$$

Denote  $n_{\max}$  as the maximum number of roadside CB-nodes arranged on. Apparently, 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 as many nodes as possible which are not used in the whole scheduling time,

we will get the optimal solution. That is, we are trying to find CB-nodes  $s_i$  that satisfy  $y_{s_i}(t) = 0$  when each vehicle passes through the entire road. We can set a binary variable  $z_i$  to indicate whether the node on the road is valid or not, i.e.,

$$z_i = \begin{cases} 1, & \exists y_{s_i}(t) = 1, 0 \leq t \leq T, \\ 0, & \forall y_{s_i}(t) = 0, 0 \leq t \leq T. \end{cases} \quad (12)$$

Based on the above discussions, we can get the formula for the final optimization cost, that is,

$$\begin{aligned} \min \quad & \sum_{i=1}^{n_{\max}} z_i, \\ \text{s.t.} \quad & (1), (3) - (12). \end{aligned} \quad (13)$$

However, notice that in Equation (13), we do not know which specific CB-node is in each set  $S_j$ , and the number of all sets  $m$  may be a very large number. We also notice that  $x_{s_i}(t)$ ,  $y_{s_i}(t)$  are continuous variables about time  $t$ , which means we have infinite variables. So Equation (13) cannot be solved directly. We need to find some way to reformulate the problem model so that it can be solved.

**3.2. Problem Refinement.** In Section 3.1, we give the problem formulation. However, this problem cannot be solved directly. We need to reformulate the problem model for solving it. In this subsection, we will give the problem model reformulation.

We notice that for the problem model (13), 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. So the CB-node set  $S_j$  is a very important variable. If we can design an algorithm for establishing suitable  $S_j$ , then we may find an easy way to solve Equation (13). To do that, we need to answer three problems: (i) How many parts we should divided at least for  $D$ ? (ii) For each CB-node set  $S_j$ , how many nodes should be included? (iii) Are there any CB-nodes in different CB-node sets?

We now discuss the first problem. Notice that the vehicle usually travels with a constant speed on roads. Based on this, we can simply assume that the vehicle travels with a speed  $v$  on the whole time  $T$ , then we have  $v \geq v_{\max} = L/T$ . Define the amount of data transmitted by each part as  $D(S_j)$ . Since the transmission radius of the CB-node is  $R_s$ , the time of each transmission of the vehicle is the time when the vehicle passes through the transmission range of the CB-node which is  $2R_s$ . Therefore, it should be ensured that the vehicle completes the transmission within  $2R_s/v_{\max}$  time.

Then, assuming that the transmission range of the CB-nodes in each segment is not intersected with the other segments, we will equally divide the whole road for  $h \geq h_{\min} = L/2R_s$  parts at least, which means we can divide the whole road equally into  $h(=m)$  path parts, and in each path part  $l_j$ , we will arrange a set  $S_j$  for helping transmitting  $D(S_j)$  data to the edge server. We also notice that when the vehicle enter-

ing a path part, the distance between it and the CB-nodes in this part will not change too much. So we can consider  $d_{v \rightarrow s_i}(t)$  as a constant  $d_v$  approximately, and the data transmission rate  $r_{v \rightarrow s_i}^{S_j}$  as a constant  $r_v$  approximately.

For the second problem, since the number of CB-nodes that is needed for each set is decided by the distance between the edge server and the set, and now we have a known  $S_j$  that is arranged for  $l_j$ , we will approximately use the distance between the center point of  $l_j$  and the edge server as the distance between  $S_j$  and the edge server. Denoting the distance as  $d(S_j)$ , and denoting the number of CB-nodes that is needed as  $n(S_j)$ , we have

$$n(S_j) = \left\lceil \frac{d(S_j)}{R_s} \right\rceil. \quad (14)$$

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

Then, we have

$$D(S_j) = \frac{D}{h} = r_v \cdot t_j \leq W \log_2 \left( 1 + \sigma_{v \rightarrow s_i}^{S_j}(t_j) \right) \cdot t_j. \quad (15)$$

Notice that 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.

In Section 3.2, we segmented the time and road and linearized the NP-hard problem in the previous section to facilitate the subsequent solution.

For the third problem, does the same CB-node exist in different sets of CB-nodes? The result of this 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 sets of CB-nodes as a cross-bit CB-node. In the following, we will set up an algorithm named as the ICBND algorithm. And this algorithm describes the steps of segmentation, and it considers that the same CB-node exists in multiple different sets of nodes. In order to approximate the optimal total number of CB-nodes, according to the number of segments, the minimum number of CB-nodes that is needed for each segment to work separately is obtained. Then, the number of CB-nodes existing in multiple different CB-node sets is obtained. The number of repeated CB-nodes is removed to obtain the optimal total number of CB-nodes. The specific steps are described in Section 3.3.

**3.3. Algorithms.** For the third problem, we notice the whole road has been divided into  $h (\geq h_{\min})$  path parts. We only have a requirement of the minimum number of path parts and not a maximum one. So in the simulation, we will set a suitable maximum number of path parts (i.e.,  $h_{\max}$ ) and try to find the optimal one between  $h_{\min}$  and  $h_{\max}$ . 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

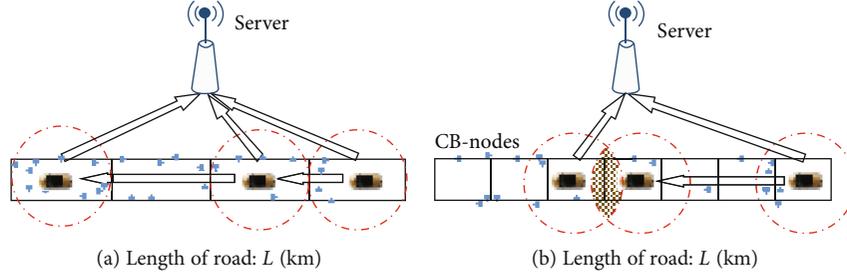


FIGURE 3: CB-node layout scheme.

CB-node sets can be in one vehicle's transmission range (see Figure 3). If the length of each segment is equal to the transmission range of the CB-node, there will be no intersection of the transmission range between the two segments, as shown in Figure 3(a). If the length of each segment is less than the transmission range of the CB-node, there will be an intersection of the transmission range between the two segments, as shown in the shaded section in Figure 3(b). In these situations, in order to describe the problem more conveniently below, we assume that the same CB-node with different sets of CB-nodes is a cross-bit CB-node; if we put the cross-bit CB-nodes in the common parts, we will save more CB-nodes.

Based on these discussions, we will try to propose a heuristic algorithm to solve this problem. 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 algorithm.

First, initialize  $h_{\max}$ ,  $h_{\min}$ . Determine that the road is divided into segment  $h$ , and calculate the distance from the center of each segment to the edge server. Then, the number of CB-nodes required for each segment is calculated according to Equation (6), and the number of CB-nodes required for each segment is temporarily stored in an array.

Second, since the transmission range of each CB-node is fixed; the length of each segment affects the existence of the same CB-node in several different sets of CB-nodes. The longer the length of the segment, the less likely the CB-node is to exist in multiple CB-node sets. We refer to CB-nodes with the same CB-node in different sets of CB-nodes as CB-nodes of cross-position. Input the broadcast range and segment length of the CB-node to get the number of cross-bit CB-nodes. We define the number of CB-nodes at the intersection of segment  $l_j$  and segment  $l_{j+1}$  as  $x_j$ . In the previous step, we figure out the number of CB-nodes needed for each segment, then we place as many CB-nodes at the intersection as possible to improve the utilization rate of CB-nodes and reduce costs. A CB-node is placed outside the crossing position, and the remaining CB-nodes are placed in the crossing position.

Third, after we get the number of cross-bit CB-nodes, each line segment has at least one receiving CB-node, and other CB-nodes can be placed on the intersection of the two line segments.

Fourth, add the minimum number of CB-nodes in each segment and the number of CB-nodes at the intersection to get the minimum value of the total number of CB-nodes.

**3.4. Complexity.** We first show the complexity for the selection step of the number of segments  $h$ . Since we need to go through all possible segment schemes, the number of iterations is  $h_{\max} - h_{\min} + 1$ . Define  $f = h_{\max} - h_{\min} + 1$ , then the complexity of this step is  $O(fn)$ .

Then, we show the minimum number of CB-nodes in each segment scheme. Since this step is a selection step nested within the first step, the complexity of this step is  $O(n^2)$ . And we show the complexity for polynomial in each iteration:

- (i) First, we calculate the distance between the vehicle and the edge server in an array, then calculate the minimum number of CB-nodes required for each segment by the formula in an array. The complexity of this part is  $O(hn)$
- (ii) Second, we need to calculate the number of cross-bit CB-nodes  $x_j$  and the number of CB-nodes except  $x_j$  in each segment. Generally, one CB-node can be placed in each segment except the intersection position, and the remaining number of CB-nodes can be used as the  $x_j$  value. The complexity of this part is  $O(hn)$
- (iii) Third, we need to go through all segments and add the number of CB-nodes of each segment and all the number of cross-bit CB-nodes. The complexity of this part is  $O(hn)$

In summary, the time complexity of our algorithm is  $O(fhn^2)$ .

## 4. Simulation

In this section, we will present the simulation results. We will first give a specific layout scheme for a particular network and then give the comparison results of more network schemes. The parameters involved are set as follows, the straight-line distance between the edge server and the road is  $a = 100$  m. The noise power  $N_0$  is  $10^{-7}$  W, and the road strength loss factor  $\lambda = 3$ . The total bandwidth of road strength  $W = 3.5$  GHz. The speed limit in urban areas is

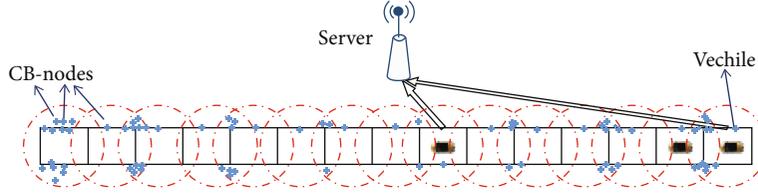


FIGURE 4: The optimal CB-node layout scheme in a specific scenario.

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

1: Initial  $x = 0$ ;

2: Initial  $j = 1, h = h_{\min}$ ;

3: **Repeat**

4: **Repeat**

5: Calculate the number of cross-bit CB-nodes  $x$ ;

6: Calculate the distance between the vehicle and the edge server at time  $t$ :  $n(S_j)$ ;

7: Calculate the number of CB-nodes in the each region:  $n(S_j) = \lceil d(S_j)/R_s \rceil$ ;

8: Determine the relation between  $R_s$  and the value between  $h_{\min}$  and  $h_{\max}$ , then calculate that the same CB-node exists in several different sets of CB-nodes;

9: Calculate the value of  $x_j$ , subtract  $x_j$  from the number of CB-nodes in this segment:  $n(S_j) = n(S_j) - x_j$ ; sum = sum +  $n(S_j)$ ;

10: sum = sum +  $n(S_j)$ ;

11: **Until** the vehicle ran the last part of the road,  $j = h$ ;

12: sum = sum +  $\sum x_j$ ;

13: Get one kind of task assignment scheme

14: **Until**  $h = h_{\max}$ ;

15: Select the best assignment scheme to be the assignment scheme for this time slice.

ALGORITHM 1: Algorithm for Iterative Coherent Beamforming Node Design.

TABLE 2: The total number of CB-nodes in a scheme with cross-bit CB-node.

Serial number	$h$	Total number of CB-nodes	Serial number	$h$	Total number of CB-nodes	Serial number	$h$	Total number of CB-nodes
1	14	104	2	15	76	3	16	76
4	17	85	5	18	83	6	19	94
7	20	92	8	21	102	9	22	100
10	23	111	11	24	110	12	25	120
13	26	118	14	27	131	15	28	126
16	29	95	17	30	94	18	31	105
19	32	103	20	33	101	21	34	115
22	35	112	23	36	112	24	37	123
25	38	120	26	39	121	27	40	131
28	41	131	29	42	126	30		

40 m/s, and the speed limit on highways is 110 m/s. Therefore, a range of vehicle speed  $v$  is set as [40,110]. Here, we take the speed as 30 m/s. Denote the vehicle's broadcast range as the CB-node's broadcast range.

*4.1. A Special Case with CB-Node Layout.* In this section, under the condition that the road length is  $L = 4000$  meters, the transmission power  $P_s$  of the CB-node is 0.3 W, and the broadcast radius data is  $R_s = 144$  meters, we will calculate the optimal total number of CB-nodes and simulate the optimal CB-node layout scheme (see in Figure 4).

We use Algorithm 1 to compute data for a series of scenarios with a cross-bit CB-node, and we calculate a set of data that is a scheme without a cross-bit CB-node. The data of the two schemes are recorded in Tables 2 and 3.

Table 2 is the scheme with cross-bit CB-nodes, and Table 3 is the scheme without cross-bit CB-nodes.  $h$  is the number of line segments divided by the road, and sum is the total number of CB-nodes arranged by the road. According to the data in Tables 2 and 3, the total number of CB-nodes in Table 2 is always less than the total number of CB-nodes in Table 3, so the scheme with cross-bit CB-

TABLE 3: The total number of CB-nodes in a scheme without cross-bit CB-node.

Serial number	$h$	Total number of CB-nodes	Serial number	$h$	Total number of CB-nodes	Serial number	$h$	Total number of CB-nodes
1	14	104	2	15	113	3	16	122
4	17	127	5	18	136	6	19	143
7	20	150	8	21	157	9	22	168
10	23	173	11	24	182	12	25	189
13	26	196	14	27	209	15	28	210
16	29	217	17	30	224	18	31	231
19	32	240	20	33	247	21	34	258
22	35	263	23	36	270	24	37	281
25	38	284	26	39	295	27	40	300
28	41	309	29	42	314	30		

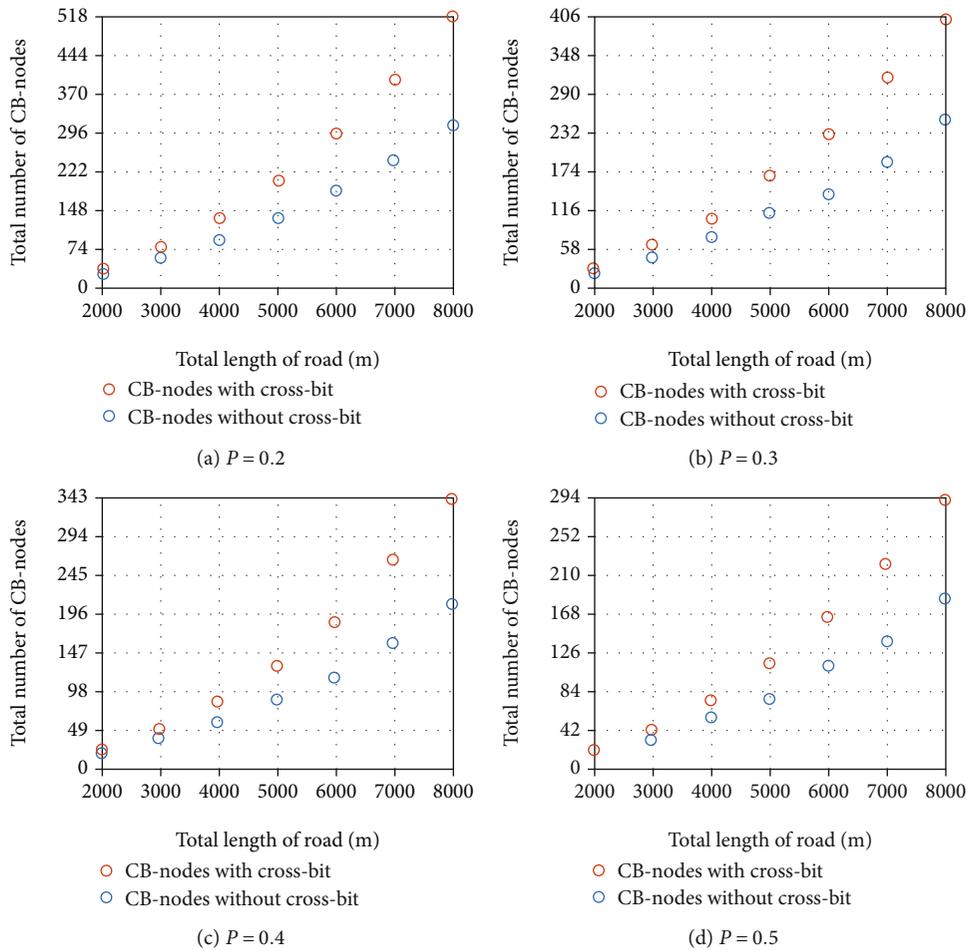


FIGURE 5: Comparisons for the total number of optimal CB-nodes under different levels of power and different path lengths.

nodes has advantages. Table 2 shows that when  $h$  is 15, the total number of CB-nodes is optimal, and the optimal scheme is one server and the total number of CB-nodes is 98. Based on this, we adopt the optimal CB-node layout

scheme to simulate the layout of real road CB-nodes, as shown in Figure 4.

In the above fixed parameter scenario, the optimal CB-node layout plan is shown in Figure 4. The number of CB-

nodes in each segment can meet the requirements of vehicle transmission data. We try to place as many CB-nodes in the intersection as possible, and the CB-nodes outside the intersection should be placed as little as possible. CB-nodes are randomly placed in fixed areas. We can see that for the CB-node layout, the closer to the edge server, the less CB-nodes are arranged, and the farther away from the edge server, the more CB-nodes are arranged.

According to market research, CB-node prices range from about 5.7 dollars to 14.3 dollars. Here, we set the cost of a CB-node at 15 dollars. The cost of a 5G base station ranges from about 28571 dollars to 71429 dollars, so we set the cost of a 5G base station at 28000 dollars. The coverage of 5G base stations is very small. For normal communication, a 5G base station needs to be deployed every 200 meters. According to the data in Table 2, the optimal total number of CB-nodes is 76 and the optimal scheme is 76 CB-nodes and one edge server. According to this arrangement, the optimal cost of the scheme with cross-bit CB-nodes we need is about 29140 dollars. The length of the road is  $L = 4000$  meters, so 20 5G base stations are needed and the cost is about 560000 dollars. As a result, we could save about 530860 dollars based on our plan layout.

**4.2. General Case.** In this section, to make the experimental results more realistic; we change  $P_s$  to get four sets of data. First, we collect a series of  $L$  values, from 2000 meters to 8000 meters, including 2000 meters, 3000 meters, 4000 meters, 5000 meters, 6000 meters, 7000 meters, and 8000 meters. Then, according to the formula  $R_s = \sqrt[3]{P_s/\beta N_0}$ , by changing the power of CB-node  $P_s$ , from 0.2 W to 0.5 W, including 0.2 W, 0.3 W, 0.4 W, and 0.5 W, we make the value of  $R_s$  take 126 meters, 144 meters, 159 meters, and 170 meters. After the experiment, a series of optimal CB-node values are obtained, as shown in Figure 5.

In Figure 5, the blue circle represents the total number of CB-nodes required for a scenario with cross-bit CB-nodes, and the red circle represents the total number of CB-nodes required for a scenario without cross-bit CB-nodes. Whether you change the length of the road or the transport range of CB-node, the blue circle is always less than the red circle. It can be seen that the total number of CB-nodes required by the scheme with cross-bit CB-nodes is the optimal, so the cost is the lowest.

As shown in Figure 5(b), under a series of  $L$  scenarios, the optimal total number of CB-nodes obtained by the scheme with cross-bit CB-nodes is 24, 46, 76, 112, 141, 189, and 250, respectively. The corresponding costs are approximately 28360 dollars, 28690 dollars, 29140 dollars, 29680 dollars, 30115 dollars, 30835 dollars, and 31750 dollars. When  $L$  values are 2000 meters, 3000 meters, 4000 meters, 5000 meters, 6000 meters, 7000 meters, and 8000 meters, the number of 5G base stations required in the layout plan of 5G base stations is 10, 15, 20, 25, 30, 35, and 40, respectively. The corresponding costs are 280000 dollars, 420000 dollars, 560000 dollars, 700000 dollars, 840000 dollars, 980000 dollars, and 1120000 dollars, respectively. Based on this, it can be seen that adopting our method can greatly reduce the cost of infrastructure.

## 5. Conclusion

In this work, we study the use of coherent beamforming technology to reduce communication costs. 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. We propose an effective heuristic algorithm ICBND, using the iterative method to calculate the total number of the minimum CB-nodes on the whole road. Specifically, ICBND divides the road into  $h$  segments, calculates the minimum number of CB-nodes for each segment, and sums them up, which is easy to achieve in practice. In the simulation experiment, we compare the scheme with the cross-bit CB-node, the scheme without the cross-bit CB-node, and the scheme of the 5G base station layout. In addition, comparative experiments show that the arrangement of the minimum number of CB-nodes of ICBND has stable and superior performance.

## Data Availability

There is no data set for this article.

## Disclosure

A preliminary version of the material in this paper has been presented at the conference in WASA 2020 (International Conference on Wireless Algorithms Systems and Applications).

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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## References

- [1] Z. Cai, X. Zheng, and J. Yu, "A differential-private framework for urban traffic flows estimation via taxi companies," *IEEE Transactions on Industrial Informatics*, vol. 15, no. 12, pp. 6492–6499, 2019.
- [2] Z. Xiong, W. Li, Q. Han, and Z. Cai, "Privacy-preserving auto-driving: a GAN-based approach to protect vehicular camera data," in *2019 IEEE International Conference on Data Mining (ICDM)*, pp. 668–677, Beijing, China, 2019.
- [3] X. Guan, Y. Huang, Z. Cai, and T. Ohtsuki, "Intersection-based forwarding protocol for vehicular ad hoc networks," *Telecommunication Systems*, vol. 62, no. 1, pp. 67–76, 2016.
- [4] L. Claussmann, M. Revilloud, D. Gruyer, and S. Glaser, "A review of motion planning for highway autonomous driving," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 5, pp. 1826–1848, 2020.

- [5] Z. Cai and T. Shi, "Distributed query processing in the edge assisted IoT data monitoring system," *IEEE Internet of Things Journal*, pp. 1–1, 2020.
- [6] X. Hou, Z. Ren, J. Wang et al., "Reliable computation offloading for edge-computing-enabled software-defined IoV," *IEEE Internet of Things Journal*, vol. 7, no. 8, pp. 7097–7111, 2020.
- [7] R. Xie, Q. Tang, Q. Wang, X. Liu, F. R. Yu, and T. Huang, "Collaborative vehicular edge computing networks: architecture design and research challenges," *IEEE Access*, vol. 7, pp. 178942–178952, 2019.
- [8] J. Wang, Z. Cai, and J. Yu, "Achieving personalized k-anonymity-based content privacy for autonomous vehicles in CPS," *IEEE Transactions on Industrial Informatics*, vol. 16, no. 6, pp. 4242–4251, 2020.
- [9] H. Peng, Q. Ye, and X. Shen, "Spectrum management for multi-access edge computing in autonomous vehicular networks," *IEEE Transactions on Intelligent Transportation Systems*, vol. 21, no. 7, pp. 3001–3012, 2020.
- [10] W. Na, S. Jang, Y. Lee, L. Park, N. Dao, and S. Cho, "Frequency resource allocation and interference management in mobile edge computing for an internet of things system," *IEEE Internet of Things Journal*, vol. 6, no. 3, pp. 4910–4920, 2019.
- [11] Q. Cui, J. Zhang, X. Zhang, K. Chen, X. Tao, and P. Zhang, "Online anticipatory proactive network association in mobile edge computing for IoT," *IEEE Transactions on Wireless Communications*, vol. 19, no. 7, pp. 4519–4534, 2020.
- [12] Z. Cai and Z. He, "Trading private range counting over big IoT data," in *2019 IEEE 39th International Conference on Distributed Computing Systems (ICDCS)*, pp. 144–153, Dallas, TX, USA, 2019.
- [13] Z. Cai and X. Zheng, "A private and efficient mechanism for data uploading in smart cyber-physical systems," *IEEE Transactions on Network Science and Engineering*, vol. 7, no. 2, pp. 766–775, 2020.
- [14] M. N. H. Nguyen, C. W. Zaw, K. Kim, N. H. Tran, and C. S. Hong, "Let's share the resource when we're co-located: collocation edge computing," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 5, pp. 5618–5633, 2020.
- [15] S. Huang, B. Lv, R. Wang, and K. Huang, "Scheduling for mobile edge computing with random user arrivals-an approximate MDP and reinforcement learning approach," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 7, pp. 7735–7750, 2020.
- [16] S. A. A. Shah, E. Ahmed, M. Imran, and S. Zeadally, "5G for vehicular communications," *IEEE Communications Magazine*, vol. 56, no. 1, pp. 111–117, 2018.
- [17] A. Gupta and R. K. Jha, "A survey of 5G network: architecture and emerging technologies," *IEEE Access*, vol. 3, pp. 1206–1232, 2015.
- [18] L. Chettri and R. Bera, "A comprehensive survey on internet of things (IoT) toward 5G wireless systems," *IEEE Internet of Things Journal*, vol. 7, no. 1, pp. 16–32, 2020.
- [19] S. Li, L. Xu, and S. Zhao, "5G internet of things: a survey," *Journal of Industrial Information Integration*, vol. 10, pp. 1–9, 2018.
- [20] X. Cheng, C. Chen, W. Zhang, and Y. Yang, "5G-enabled cooperative intelligent vehicular (5GenCIV) framework: when Benz meets Marconi," *IEEE Intelligent Systems*, vol. 32, no. 3, pp. 53–59, 2017.
- [21] M. Fakhri, A. Diallo, P. Le Thuc, R. Staraj, O. Mourad, and E. Rachid, "Characteristic mode theory to enhance the isolation level for full-duplex 5G in mobile handsets," in *2019 16th International Symposium on Wireless Communication Systems (ISWCS)*, pp. 81–85, Oulu, Finland, 2019.
- [22] S. Jayaprakasam, S. K. Abdul Rahim, C. Y. Leow, and M. F. Mohd Yusof, "Beampattern optimization in distributed beamforming using multiobjective and metaheuristic method," in *2014 IEEE Symposium on Wireless Technology and Applications (ISWTA)*, pp. 86–91, Kota Kinabalu, Malaysia, 2014.
- [23] S. Jayaprakasam, S. K. A. Rahim, and C. Y. Leow, "Distributed and collaborative beamforming in wireless sensor networks: classifications, trends, and research directions," *IEEE Communications Surveys Tutorials*, vol. 19, no. 4, pp. 2092–2116, 2017.
- [24] G. Sun, Y. Liu, J. Zhang, A. Wang, and X. Zhou, "Node selection optimization for collaborative beamforming in wireless sensor networks," *Ad Hoc Networks*, vol. 37, pp. 389–403, 2016.
- [25] B. Bjar Haro, S. Zazo, and D. P. Palomar, "Energy efficient collaborative beamforming in wireless sensor networks," *IEEE Transactions on Signal Processing*, vol. 62, no. 2, pp. 496–510, 2014.
- [26] W. Xiong, Z. Lu, B. Li et al., "A self-adaptive approach to service deployment under mobile edge computing for autonomous driving," *Engineering Applications of Artificial Intelligence*, vol. 81, pp. 397–407, 2019.
- [27] L. Zhang, W. Cao, X. Zhang, and H. Xu, "MAC2: enabling multicasting and congestion control with multichannel transmission for intelligent vehicle terminal in internet of vehicles," *International Journal of Distributed Sensor Networks*, vol. 14, no. 8, Article ID 155014771879358, 2018.
- [28] L. Wang, J. Gui, X. Deng, F. Zeng, and Z. Kuang, "Routing algorithm based on vehicle position analysis for internet of vehicles," *IEEE Internet of Things Journal*, vol. 7, no. 12, pp. 11701–11712, 2020.
- [29] F. Wei, S. Zeadally, P. Vijayakumar, N. Kumar, and D. He, "An intelligent terminal based privacy-preserving multi-modal implicit authentication protocol for internet of connected vehicles," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–13, 2020.
- [30] G. Sun, L. Song, H. Yu, X. Du, and M. Guizani, "A two-tier collection and processing scheme for fog-based mobile crowdsensing in the internet of vehicles," *IEEE Internet of Things Journal*, vol. 8, no. 3, pp. 1971–1984, 2021.
- [31] X. Huang, K. Xu, Q. Chen, and J. Zhang, "Delay-aware caching in internet of vehicles networks," *IEEE Internet of Things Journal*, no. article 1, 2021.
- [32] J. Gao, K. O. Obour Agyekum, E. B. Sifah et al., "A blockchain-SDN-enabled internet of vehicles environment for fog computing and 5G networks," *IEEE Internet of Things Journal*, vol. 7, no. 5, pp. 4278–4291, 2020.
- [33] X. Xu, X. Zhang, X. Liu, J. Jiang, L. Qi, and M. Z. A. Bhuiyan, "Adaptive computation offloading with edge for 5G-envisioned internet of connected vehicles," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–10, 2020.
- [34] M. LiWang, S. Dai, Z. Gao, X. Du, M. Guizani, and H. Dai, "A computation offloading incentive mechanism with delay and cost constraints under 5G satellite-ground IoV architecture," *IEEE Wireless Communications*, vol. 26, no. 4, pp. 124–132, 2019.
- [35] S. Wan, R. Gu, T. Umer, K. Salah, and X. Xu, "Toward offloading internet of vehicles applications in 5G networks," *IEEE Transactions on Intelligent Transportation Systems*, pp. 1–9, 2020.

- [36] Y. Shi and Y. E. Sagduyu, "Coherent communications in self-organizing networks with distributed beamforming," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 1, pp. 760–770, 2020.
- [37] J. A. Nanzer, R. L. Schmid, T. M. Comberiate, and J. E. Hodkin, "Open-loop coherent distributed arrays," *IEEE Transactions on Microwave Theory and Techniques*, vol. 65, no. 5, pp. 1662–1672, 2017.
- [38] C. Bai, X. Zhang, X. Qiao, Y. Sang, H. Zhong, and M. Wan, "Ultrasound transcranial imaging based on fast coherent-time-delay and correlative pixel-based beamforming," in *2018 IEEE International Ultrasonics Symposium (IUS)*, pp. 1–4, Kobe, Japan, 2018.
- [39] D. Scherber, P. Bidigare, R. O'Donnell et al., "Coherent distributed techniques for tactical radio networks: enabling long range communications with reduced size, weight, power and cost," in *MILCOM 2013-2013 IEEE military communications conference*, pp. 655–660, San Diego, CA, USA, 2013.
- [40] H. Deng, Z. Geng, and B. Himed, "Mimo radar waveform design for transmit beamforming and orthogonality," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 52, no. 3, pp. 1421–1433, 2016.
- [41] T. P. Bidigare, U. Madhow, D. R. Brown et al., "Wideband distributed transmit beamforming using channel reciprocity and relative calibration," in *2015 49th Asilomar conference on signals, systems and computers*, pp. 271–275, Pacific Grove, CA, USA, 2015.
- [42] A. G. Marques, Xin Wang, and G. B. Giannakis, "Minimizing transmit power for coherent communications in wireless sensor networks with finite-rate feedback," *IEEE Transactions on Signal Processing*, vol. 56, no. 9, pp. 4446–4457, 2008.