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An Optimal Wireless Transmission Strategy based on Coherent Beamforming and Successive Interference Cancellation for Edge Computing

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***Abstract*—In general, edge devices and edge servers in edge computing environment communicate with each other by wireless network, which put forward a high requirement for end-to-end wireless communication performance. In this paper, we propose an optimal strategy by combining the coherent beamforming (CB) technique and the successive interference cancellation (SIC) technique for improving the performance of the edge device communications. CB technique can be used for expanding the transmitter's transmitting range, while SIC technique can be used for improving the receiver's receiving ability. However, when these two techniques are used jointly, interference will occur between transmitters and receivers, which makes the CB-SIC strategy hard to be designed. We first give the mathematical model based on CB-SIC and show it is difficult to solve directly. Then, we design a heuristic algorithm called time slot loop allocation (TSLA) algorithm. TSLA is based on greedy strategy to obtain an approximate optimal solution. By using TSLA, the whole scheduling time will be divided into many time slots. In each time slot, we try to make as many edge devices as possible to transmit data to the server. These can increase the overall data throughput. In simulation, we compare CB-SIC wireless network with CB only, SIC only, and traditional multi-hop network. Simulation results show that the TSLA algorithm can improve the end-to-end communication performance in edge computing environment.**

***Index Terms*—edge computing, wireless network, coherent beamforming, successive interference cancellation, throughput**

I. INTRODUCTION

Edge computing, as a potential technology framework, has attracted many researchers' attention [1] [2] [3]. When using edge computing, most of computing tasks from edge devices will be processed on closed edge servers, so as to reduce the delay of the computing systems and relieve the pressure of the cloud computing center. Edge computing has played an important role in some research fields, such as automatic driving [4] and Internet of things [5]. In edge computing framework, edge devices usually transmit data to edge servers by wireless communications [6] [7] [8]. Then edge servers will process these data. This means that the edge computing has a high demand for end-to-end wireless network performance. So most researchers believe that the 5G technology is the key point for the large scale application of the edge computing in the future. Therefore, many efforts have been made on this field [9] [10]. However, comparing with 4G, a 5G base station has a smaller coverage range and a higher construction cost [11] [12] [13]. Coherent beamforming (CB) technique is a technique which can expand the transmitter's transmission range by the help of some other transmitting nodes. So in this paper, we try to use CB technique for the transmitters in the edge computing environment. Since the transmission ranges are expanded, new interferences will occur at the receivers, and we need to handle them. Nowadays many interference management technologies for wireless networks have been studied, such as interference alignment [14] [15], interference cancellation and other technologies [16]. However, seldom work has been done on the edge computing environment applying 5G technology for end-to-end communications. In the paper, we try to use the successive interference cancellation (SIC) technique for the receivers in the edge computing environment. And we try to give a communication scheme for optimizing from both the senders and the receivers at the same time. We first give a glance about the CB technique and the SIC technique.

The CB technique can expand the transmitter's transmission range. Each transmission node has only a single common antenna. When transmitting, the transmission node needs several other nodes for helping. This technique can improve the power gain between long-distance nodes, so as to improve the transmission distance. Different from the collaborative beamforming technique [17] [18], the CB technique has no strict requirement for the location of nodes and does not produce high directional beams. In [19], authors have proved that for a n-transmitter (include the transmission node and

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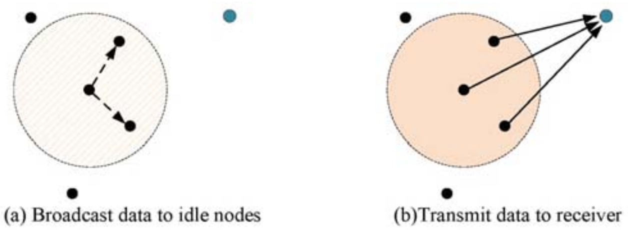


Fig. 1. Two steps of coherent beamforming communications.

the help nodes) and one receiver transmission, the power gain can reach n^2. The CB technique can be divided into two steps [19]. First, a transmitter transmits data to the neighbour nodes (see in Fig.1(a)). Second, these nodes work together for transmitting data to the receiver (see in Fig.1(b)). The CB technique has attracted the attention of many researchers. In [20], a CB technique scheme with minimum transmitting power is designed for multi-input-single-output (MISO) communication with limited rate feedback. In [21], authors design a distributed beamforming scheme in the wireless sensor network environment, which enlarges the transmission range of nodes in the network and reduces the energy consumption. In [22], authors apply the CB technique to MISO to minimize transmission power. In [19], authors apply the CB technique to MIMO scheduling, which further improves data throughput comparing with MISO. If the CB technique is applied to end-to-end communication in edge computing, the communication performance will be greatly improved.

The SIC technique can be classified as one of interference management techniques [23] and let the receivers receive several transmitters' signals simultaneously. Nowadays Interference Management techniques have been widely used in wireless communications, such as interference alignment [24] [25], interference neutralization [26], interference cancellation [23]. By dealing with the interference, we can increase the data throughput of the wireless network. The SIC technique can make a receiver to take multiple interfering signals from different transmitters and decode each signal iteratively as long as the SINR is greater than a threshold. Receiving multiple signals at the same time makes the data throughput greatly increased. In [27], authors propose a multi-hop wireless network cross layer optimization framework based on SIC. The results show that the network throughput is improved about 47% compared with the scheme without SIC. In [28], authors propose a heuristic algorithm for multi hop wireless network routing, and use SIC to obtain a bandwidth sensitive high throughput protocol. Simulation results show that the throughput of this algorithm is 29.62% higher than that of the comparison algorithm. In [29], authors use SIC technique to optimize the wireless multi-hop network in full-duplex environment, and achieve a higher data throughput. In [30], authors propose a cross layer optimization framework based on DoF and SIC, which improves the data throughput of MIMO network.

According to our knowledge, few work have considered to use the CB technique and the SIC technique jointly for improving the end-to-end communication ability for edge computing. In our previous work [31], we apply collaborative beamforming technique for wireless networks. In this wireless network, there are many pairs of transmitting nodes and receiving nodes. Transmitting nodes use collaborative beamforming technique to transmit data to receiving nodes. We design a heuristic algorithm to obtain the approximate optimal solution. Experimental results show that compared with multi hop networks, collaborative beamforming can greatly improve data throughput. In this paper, we consider combining CB and SIC technique to optimize the end-to-end data transmission of edge computing. We assume that there are multiple nodes and an edge server in a wireless network. Nodes that need to transmit data to the edge server are edge devices, and the rest are idle nodes. In the whole transmission process, the transmitters first transmit their data to their neighbour idle nodes, and then use CB technique to improve the transmission range and transmit their data to the edge server. The edge server uses SIC technique to receive multiple signals at the same time. We first build a mathematical model for CB-SIC network. This model is difficult to solve directly. Therefore, we design a heuristic algorithm called time slot loop allocation (TSLA) algorithm. TSLA is based on greedy strategy to assign time slots for each transmission node. We get an approximate optimal solution and improve the data throughput by determining the transmission state of each node in all time slots.

The rest of this paper is organized as follows: In section II, we give the mathematical model of the whole CB-SIC wireless network, and find it a NP-hard problem. In section III, we design a heuristic scheduling algorithm based on a greedy strategy to get an feasible solution. In section IV, we give the simulation results and analyze them. In section V, we summarize this paper.

II. THE MATHEMATICAL MODEL

We describe the throughput maximization problem for coherent beamforming wireless network based on SIC and give the mathematical model. Consider a CB-SIC wireless network in a two-dimensional area with n edge devices and one edge server. Edge device needs to transmit data to the edge server. We do not consider that nodes can transmit data to the edge server directly. That is, suppose all edge devices have a long distance from the edge server so that no one can transmit data without the CB technique In addition, there are m idle nodes with the same specifications as edge devices for helping transmitting by CB technique. Denote $s_i(1 \leq i \leq n)$ as the edge device, and the set of these nodes is N. Denote $s_j(n+1 \leq j \leq n+m)$ as the idle node and the set of idle nodes is M. Denote s_0 as the edge server. Suppose data transmissions are scheduled in time frames, where each frame $\mathcal{T}$ is divided into f time slots. Denote $t_k(1 \leq k \leq f)$ as these time slots.

Notice that by using CB technique, an edge device will use two steps for a transmission in two different time slots. First, it broadcasts its data to its neighbour idle nodes in the previous time slot. Second, it and its neighbour idle nodes transmit data to the edge server by CB technique in the later time slot. For the first step, we define a binary scheduling variable $x_i(k)$ to indicate an edge device s_i's broadcasting in time slot t_k. For the second step, we define a binary scheduling variable $y_i(k)$ for the CB transmission in time slot t_k, and define $S_i(k)$ as the set of nodes for helping s_i using CB technique in t_k (including idle nodes and the edge device s_i). We have

$$x_i(k) = \begin{cases} 1: & \text{if node } s_i \text{ broadcast data in time slot } t_k; \\ 0: & \text{otherwise.} \end{cases}$$

$$y_i(k) = \begin{cases} 1: & \text{if node } s_i \text{ transmit data to } s_0 \text{ in time slot } t_k; \\ 0: & \text{otherwise.} \end{cases}$$

There will be multiple edge devices working at the same time. Some edge devices broadcast data to the surrounding idle nodes, and some edge devices transmit data to edge servers by CB communication. In a time slot t_k, an edge device s_i can either transmit data to the edge server or broadcast data to its neighbours, but these two steps cannot be started simultaneously. We have

$$x_i(k) + y_i(k) \leq 1 \quad (s_i \in N, 1 \leq k \leq f) \tag{1}$$

Notice that for the first step, s_i just simply broadcasts its data to S_i. While in the second step, the edge server s_0 can receive several data from different transmitters by CB-SIC technique. The CB technique can expand the transmission range by increasing the overall transmission power, which depends on the number of nodes involved in transmission and the distance between each node and the edge server. We have Lemma 1.

Lemma 1 *If s_i transmit data to a receiver by CB technique with the help of $S_i(k)$, where $S_i(k)$ is the set of nodes participating in the CB transmission at time slot t_k, and all nodes transmission powers are the same P, then the power of the receiver s_0 can be calculated by $P_D = (\sum_{s_j \in S_i(k)} h_{j0})^2 P$, where ${h_{j0}}^2$ is the channel gain between s_j and s_0.*

Based on Lemma 1, we denote the CB power of edge device s_i at the s_j is $P_{ij} = (\sum\limits_{s_t \in S_i(k)} h_{tj})^2 P$. Then we can get the received SINR of the edge server when using SIC. We have

$$SINR^k_{S_i(k) \to s_0} \cdot y_i(k) = \frac{P_{i0} \cdot y_i(k)}{N_0 + \sum\limits_{P_{i0} \geq P_{t0}}^{s_l \neq s_i} P_{t0} \cdot y_l(k)} \geq \beta \cdot y_i(k), \tag{2}$$

where N_0 is the noise power, W is the channel width and β is a threshold for ensuring the channel capacity.

When the edge device broadcasts to the surrounding idle nodes, interference may cause the broadcast to fail. If there are other devices broadcasting or transmitting data to the edge server at the same time slot, interference will occur. So the SINR of the idle node receiving data must be greater than β. We have

$$\begin{aligned} & SINR^k_{s_i \to s_t} \cdot x_i(k) \\ &= \frac{(h_{it})^2 P \cdot x_i(k)}{N_0 + \sum\limits_{(h_{it})^2 P \geq P_{lt}}^{s_l \neq s_i} P_{lt} \cdot y_l(k) + \sum\limits_{(h_{it})^2 \geq (h_{lt})^2}^{s_l \neq s_i} (h_{lt})^2 P \cdot x_l(k)} \\ &\geq \beta \cdot x_i(k) \quad (s_t \in S_i(k)). \end{aligned} \tag{3}$$

In different time slots, the number of idle nodes in set $S_i(k)$ is different. In some time slots, in order to meet the requirements of SIC, more idle nodes are needed in the set $S_i(k)$. But the number of idle nodes must meet the number of nodes needed for related communication. The number of idle nodes in set $S_i(k)$ must be less than the number of idle nodes in the transmission range of edge device s_i. We have

$$|T_i| \leq |S_i(k)| \leq |N_i|, \tag{4}$$

where T_i is the set of minimum nodes (include the edge device s_i and idle nodes) required to complete CB transmission, and N_i is the set of all nodes in the transmission range of s_i (include edge device s_i).

Suppose each node s_i has a transmitting data rate r_i. Denote $r_{S_i(k) \to s_0}$, $s_i \in N$, as the average data rate in the whole scheduling time $\mathcal{T}$ from edge device s_i to edge server s_0. Denote $r_{s_i \to S_i(k)}$ as the average data rate of node s_i broadcasts data. We have the relationship for flow rates of the node s_i,

$$r_i = r_{s_i \to S_i(k)} = r_{S_i(k) \to s_0} \quad (s_i \in N). \tag{5}$$

For each link, the flow rate cannot exceed the achievable average link rate, we have,

$$r_{s_i \to S_i(k)} \leq \frac{1}{f} \sum_{k=1}^{f} (C \cdot x_i(k)) \quad (s_i \in N), \tag{6}$$

$$r_{S_i(k) \to s_0} \leq \frac{1}{f} \sum_{k=1}^{f} (C \cdot y_i(k)) \quad (s_i \in N), \tag{7}$$

where C is the data rate by a successful transmission and can be calculated by $W log_2(1 + \beta)$.

Define the r_{all} is the total rate for all edge devices. Based on the above discussions, the problem model can be formulated as,

$$\begin{aligned} \max \quad & r_{all} \\ \text{s.t.} \quad & r_{all} = \sum_{i=1}^{n} r_i \\ & (1) - (7) \\ & x_i(k), y_i(k) \in \{0, 1\}, r_{s_i \to S_i(k)}, r_{S_i(k) \to s_0} \geq 0 \end{aligned} \tag{8}$$

In Equation (8), there are variables $x_i(k)$, $y_i(k)$ and $S_i(k)$. The variable $S_i(k)$ appears in the numerator and denominator of SINR formula. We can not determine the value of $S_i(k)$ directly, and we can not determine the values of $x_i(k)$, $y_i(k)$ directly either. Therefore, this problem is NP-hard in general, which is difficult to solve directly. If the values of these variables can be determined, the solution can be obtained. In section III, we design a heuristic algorithm, determine the values of these variables, and obtain the feasible solution.

III. Scheduling Algorithm

In section II, we propose the optimization objective and give the problem formulation, which is NP-hard in general. This means that it is very difficult to find an optimal solution for CB-SIC networks. Therefore, in this section, we will design a heuristic algorithm to get a feasible solution. The main idea of this heuristic algorithm are based on greedy strategy. We try to make as many edge devices as possible in each time slot to transmit data to the server. We call this heuristic algorithm as time slot loop allocation (TSLA) algorithm.

A. *Main Idea of Algorithm*

We can find that there are variables $x_i(k)$, $y_i(k)$ and $S_i(k)$ in Equation (8), which makes the problem difficult to solve. If we can determine the values of these variables, the remained problem only needs to calculate with $r_{s_i \to S_i(k)}$ and $r_{S_i(k) \to s_0}$. In this way, the problem can be solved. We can get a feasible solution. Therefore, we need to solve the following problems.

1) How to determine the number of idle node in $S_i(k)$ to obtain the appropriate transmission power?
2) After determining the number of idle nodes in $S_i(k)$, how to determine the value of $x_i(k)$, $y_i(k)$ in different time slots and get a feasible solution?
3) Can we further improve the data throughput based on the feasible solution?

We solve these problems in turn:

1) When using CB technique, the number of idle nodes participating in transmission determines the transmission power and distance. By Equation (4), we can find that the number of idle nodes in $S_i(k)$ can change from a certain range. When $|S_i(k)| > |T_i|$, each additional idle node increases the CB transmission power. This will make the receiver receive data much complex by SIC. When $|S_i(k)| = |T_i|$, the number of idle nodes is least. In order to reduce the complexity, we set the value of $|S_i(k)|$ as a fixed value and $|S_i(k)| = |T_i|$.
2) Based on $|S_i(k)| = |T_i|$, we first try to determine values of $x_i(k)$, $y_i(k)$ in a time slot, and then determine the value of variables in the next time slot. In each time slot, we start it with the smallest CB power edge device, and select the device that meets the technical requirements of SIC. We will do it in turn until all $x_i(k)$, $y_i(k)$. In this way, we get a feasible solution.
3) Due to the use of SIC, multiple edge devices can transmit data to the server at the same time. When using CB technique, the higher the value of $|S_i(k)|$, the greater the transmission power. Based on the feasible solution, we select the appropriate edge device and add the idle nodes in $S_i(k)$ to make the SINR meet the SIC requirements in a time slot. So the $y_i(k)$'s value of the edge device changes from 0 to 1. We do it in all time slot. In this way, a feasible solution with higher throughput can be obtained.

B. *Three Steps of the TLSA Algorithm*

The whole algorithm can be divided into three steps. In the following, we will first give the main idea of these steps.

a) Step 1: Initialization: We first calculate the distance between each edge device and the edge server, then get the minimum number of each idle node for each edge device, and then calculate each minimum transmission power for CB technique. We sort all edge devices according to transmission power.

b) Step 2: Time slot allocation based on minimum CB transmission power: In this step, we will allocate edge devices for each time slot based on minimum CB transmission power. Notice that in each time slot, an edge device may be in one of three states: broadcasting data to its surrounding nodes ($x_i(k) = 1$), transmitting data to the edge server by CB technique ($y_i(k) = 1$) or be in idle state ($x_i(k) = 0$ and $y_i(k) = 0$). We need to decide each edge device state for each time slot.

In detail, we first decide the state of two edge devices. For one time slot, we first select an edge device s_j and let it in transmitting data state ($y_i(k) = 1$). To do that, denote $r_{remain}(j)$ as the data which need to be while has not to be transmitting now. We will select a node with the maximum $r_{remain}(j)$ now (if there are several nodes with the same maximum $r_{remain}(j)$, we will select one randomly). Next, we select an edge device s_l and let it in the broadcasting data state. s_l's $r_{remain}(l)$ is the least.

Then, we try to decide the transmitting data state of other edge devices. we will select the next node with the minimum CB transmission power, $r_{remain}(i) > 0$ and which can transmitting data with the first node s_j together (i.e. they will satisfy the SIC requirement). We will do the step repeated until all edge devices have been verified.

Next, we try to decide the broadcasting data state. To do that, we will verify each edge device in the remain edge devices one by one. If it can broadcast in this time slot (satisfy the SIC requirement), we will let it broadcast. We do it until all edge devices have been verified. And the remain devices will be in idle state.

c) Step 3: Time slot allocation based on increasing CB transmission power: In this step, according to the feasible solution of step 2, we can further improve the data throughput and obtain the final feasible solution.

By increasing the idle nodes participating in CB transmission, the edge device's CB transmission power can be increased. By increasing CB transmission power, the edge device will satisfy the SIC requirement. It changes from non transmitting data state($y_i(k)$ = 0) to transmitting data state ($y_i(k)$ = 1). For a time slot, we first select an edge device s_i to change from non transmitting data state ($x_i(k) = 0$ and $y_i(k) = 0$, or $x_i(k) = 1$) to transmitting data state ($y_i(k)$ = 1). For the edge device s_i, there are $r_{remain}(i) > 0$. And s_i can transmit data to the edge server together with other edge devices (satisfy the SIC requirement), without affecting the transmission states of other time slots. we do it until all nodes in non transmitting data state have been verified.

The heuristic algorithm is designed based on the above three steps.

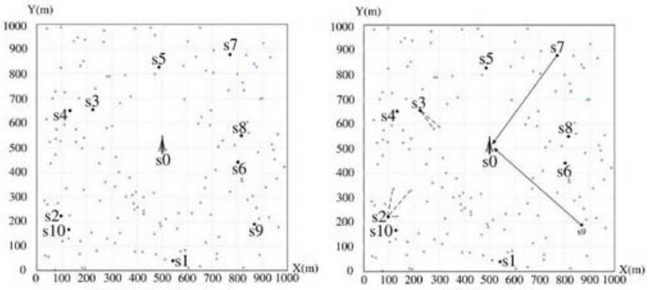
IV. SIMULATION EXPERIMENT

In this section, we give results of simulation experiments to show the performance of our algorithm and compare with other networks. We will compare with CB-only network to the advantages of CB-SIC network. For CB-SIC networks, two experimental results are given, which are minimum CB transmission power and increased CB transmission power

We deployed CB-SIC network with 5 to 10 edge devices and one edge server in a $1000m \times 1000m$ square area. There are 150 to 300 idle nodes randomly distributed to assist the edge device in coherent communication. We set P=1W, $N_0 = 10^{-15}$W, β = 1 and W=22MHz. We divided the whole transmission process into 20 time slots.

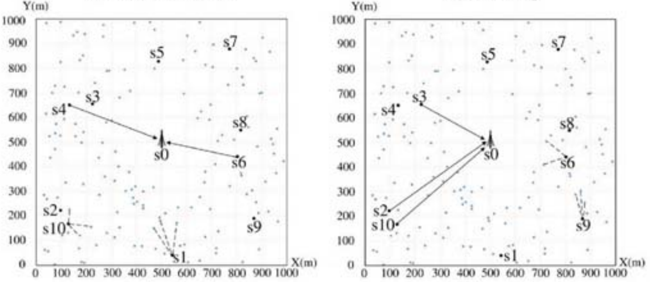
We first present detailed results of a CB-SIC network with 10 edge devices and 150 idle nodes, and compare it with CB-only networks in the same node distribution environment in Sec.4.1. Then, we provide complete results for all network instances with different number of nodes in sec.4.2.

A. Results for a CB-SIC Network with 10 Edge Devices and 70 Idle Nodes



(a) Network environment

(b) Time slot t_2



(c) Time slot t_7

(d) Time slot t_8

Fig. 2. The distribution of 10 edge devices and 150 idle nodes and transmission of different time slots.

Consider a CB-SIC network as shown in Fig.2(a). In this network, 10 edge devices are randomly distributed, and the location of the edge server is $(500, 500)$. In addition, there are 150 idle nodes in the network. With the help of idle nodes, all edge devices can directly transmit data to the edge server. In Fig.2(b), 2(c) and 2(d), we show the transmission of edge devices using increased CB power in time slot t_2, t_7 and t_8.

In Fig.2(b), we can find that edge devices s_7 and s_9 directly transmit data to the edge server by CB technique. At the same time slot, edge devices s_2 and s_3 broadcast data to the idle nodes. In Fig.2(c) and 2(d), we can also see that there are multiple edge devices transmitting data to the edge server.

In CB-only network, only one edge device in a time slot can be allowed to transmit data to the edge server. This means that the total number of time slots that all edge devices can be allowed to send data to the edge server will not exceed 20. In Table 2, we can see that in CB-SIC network, the total number of time slots that all edge devices can send data to the edge server is 48.

By comparing the experimental results in this network environment, it can be found that when using CB and SIC technique to transmit data, the average amount of data transmitted is 2440KB, which is the same network environment, the average amount of data transmitted by using CB is 950KB. The data throughput of CB-SIC network is 252% of that of CB network. In this network environment, we can find that the performance of CB-SIC network is much better than that of CB network, which confirms our idea.

B. Results for All Network Instances

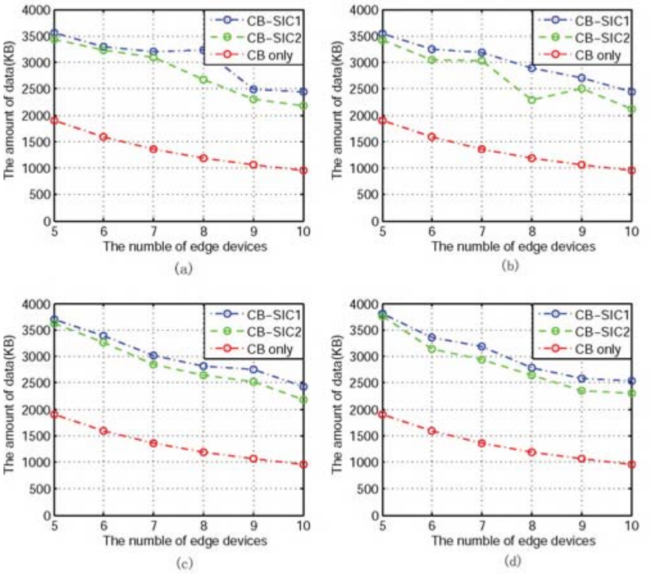


Fig. 3. More comparisons for different number of edge devices and idle nodes.(a)150 idle nodes.(b)200 idle nodes.(a)250 idle nodes.(a)300 idle nodes.

We change the number of edge devices n from 5 to 10, the number of idle nodes m from 150 to 300. So we have 24 different network instances randomly for CB-SIC network and CB-only network.

Then, according to the location and transmission rate of the nodes, we calculate the amount of data that the node transmits in all time slots, and show the average values for each network in Fig.3. In Fig.3, CB-SIC1 indicates that edge devices have a increased CB transmission power, and CB-SIC2 indicates that edge devices have a minimum CB transmission power.

From these simulation results, we can see that the throughput in CB-SIC networks is improved greatly compared with CB-only networks. No matter how the number of edge devices and idle nodes changes, the data throughput of CB-SIC network is always more than twice that of CB network.

By increasing the CB transmission power, the throughput is further improved. In Fig.3, we can find that by increasing the number of nodes participating in CB transmission, we have achieved better communication performance. The data throughput of CB-SIC1 is always greater than that of CB-SIC2. This shows that compared with using a fixed number of idle nodes, edge devices get more opportunities to transmit to the edge server.

V. CONCLUSION

In this paper, we consider in wireless network environment that edge devices need to transmit data to an edge server by CB technique. We use CB and SIC technique to increase the data throughput of the whole network. Since the designed mathematical model is NP-hard in general and can not be solved directly, we design a heuristic algorithm called TSLA algorithm to assign time slots for edge devices, and maximize the data transmitted to the edge server. Simulation results show that combining CB and SIC technique, our algorithm can increase the throughput obviously. CB technique can improve the communication performance and reduce costs. In the future, we will combine CB technique with other technologies. In this way, CB technique can play a greater role in edge computing and other environments.

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