An Incentive Mechanism Based on Bertrand Game for Opportunistic Edge Computing

QINGHUA LI\textsuperscript{1}, FENG ZENG\textsuperscript{2, (Member, IEEE)}, QING WU\textsuperscript{2}, AND JUNJIE YANG\textsuperscript{1}

\textsuperscript{1}School of Information Engineering, Lingnan Normal University, Zhanjiang 524046, China
\textsuperscript{2}School of Computer Science and Engineering, Central South University, Changsha 410083, China

Corresponding author: Feng Zeng (fengzeng@csu.edu.cn)

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ABSTRACT In a real edge network, many nodes may be selfish and unwilling to forward messages for other nodes. In this case, an incentive mechanism is needed to encourage the selfish nodes to participate in message forwarding. In this paper, we analyze the interaction between the source node and the relay node in edge opportunistic networks, and propose an incentive mechanism based on game theory to encourage the cooperation between nodes. Firstly, we define the interaction steps between the source and the relay node, which include that the source node decides the price of forwarding a message, the relay node responds the forwarding plan to the source node, and all nodes can get reward for their participant in message forwarding. We provide two-stage incentives to nodes, that is, the nodes can get reward from both receiving and forwarding messages. Since the nodes may be selfish, both the source node and the relay node want to maximize their utilities. Then, we model the cooperation between the source and the relay node as Bertrand Game, and the utility functions of the source and the relay node are defined. Furthermore, we find that the Nash Equilibrium is existed and unique, and present the best pricing scheme for the source node and the best forwarding plan for the relay node. The simulation results show that the proposed incentive mechanism can encourage the cooperation between selfish nodes, and improve the performance of routing algorithm in terms of delivery ratio and delay.

INDEX TERMS Edge computing, opportunistic network, incentive mechanism, game theory.

I. INTRODUCTION

With the development of mobile terminals and wireless technology, the Opportunistic Edge Network [1] is increasingly becoming the hot research topic. The opportunistic edge network is evolved by wireless self-organizing network and Delay Tolerant Networks (DTN) [2]. In traditional wireless ad hoc networks, it is required for data transmission that at least one complete communication link is existed between the source and destination node. However, there may be network interrupt for a long time in real environment, and the normal communications between the source and the destination cannot be guaranteed. Different from the traditional network, it does not need a complete link between the source and the destination in an opportunistic edge network, and forwarding messages between nodes are usually opportunistic and based on the movement of nodes [3]. The opportunity networks use a storage-carried-forwarding route for data transmission. That is, if the node does not find the appropriate relay node, the messages will be stored in its buffer, and it carries the messages in the movement until it finds the appropriate relay nodes, then the messages will be forwarded to the relay nodes, and with the step-by-step forwarding by some intermediate nodes, the messages arrive at the destination at last.

As we can find from the routing scheme in opportunistic edge networks, there may be many nodes taking part in the communication between the source and the destination, and the success of data transmission is based on the cooperation among nodes [4]. Consequently, the premise of data transmission is that the intermediate nodes in a routing path are willing to forward the packets. But in many applications, the mobile devices acting as the nodes in opportunistic networks are belonging to different and independent owners. Due to the constrains of nodes’ capability, memory space, battery power and many other resources, the nodes may be inclined to behave selfishly. They may only want to receive the messages
which they are interested, and refuse to receive messages which may be no use to them but good for others. If all node are rational, the nodes will show selfishness by trying to save their resources and forwarding no messages for others. In [5], the authors have shown that the selfish behavior of nodes seriously did harm to the performance of data transmission in opportunity networks, and the incentive to the nodes can improve the overall performance of network.

At present, the incentives in opportunistic networks have three categories which are TFT (Tit-for-Tat)-based mechanism [6], reputation-based mechanism [7]–[9] and credit-based mechanism [9]–[10]. The main idea of TFT-based mechanism is to use Game Theory to construct the model according to the principle of reciprocity, and the nodes forward to other nodes the data which has the same amount with the data they received from others. In real network environment, due to the asymmetric business, it is difficult to achieve good performance in TFT-based mechanisms. In the reputation incentive mechanism, the historical collaboration behavior of each node is recorded, and each node is given a reputation value to show whether it is selfish. Moreover, the value of reputation is dynamic, the nodes participating in message forwarding will gain the increasing of its reputation, and the nodes with bigger reputation value will be selected to forward the messages. However, the reputation mechanism cannot distinguish between high-confidence nodes and beliefs that are equal to or slightly higher than the legal system, resulting in poor incentive to the nodes. In the credit incentive mechanism, the source node has to pay a virtual currency to the intermediate nodes forwarding the message, the third-party management is required, and there is no difference pricing scheme for nodes.

As mentioned above, each type of incentive mechanism has its disadvantage in stimulating the nodes to forward messages for others in opportunistic routing. In this paper, we apply game theory and virtual currency to the analysis of the interaction between nodes, and propose an incentive mechanism in which node cooperation is modeled as Bertrand Game. With the defined pricing scheme and incentive mechanism, the Nash Equilibrium is achieved and each node receives its maximum utility. Different with the existing works, in the proposed mechanism, two-stage incentive is applied to message transmission. Since message transmission in a node includes two stages which are to receive the message from the source node and to forward the message to others, each node should be encouraged not only to receive messages from the source nodes, but also to forward the messages to others. The work in this paper promotes the enthusiasm of nodes to participate in message forwarding, and has the performance of data transmission improved.

The remainder of the paper is organized as follows. In Section 2, we describe and analyze the related incentive schemes. Section 3 presents the Bertrand Game based incentive mechanism in detail. In section 4, we describes pricing analysis based on Game Theory. Simulations are presented and discussed in section 5. Finally, we concludes the paper in section 6.

II. RELATED WORK

Opportunistic routing has been extensively studied, and various types of message forwarding methods and routing algorithms were proposed for “storage-carried-forwarding” data transmission with the goal of improving data delivery rate, meanwhile reducing network overhead.

Epidemic Routing [11] flooded the message to all nodes without consideration of routing overhead. Theoretically, epidemic routing had the highest success rate of data delivery. Direct Transmission [12] required that the source stored the data to be sent, and did not forward the data to any nodes but the destination. Direct transmission had the lowest overhead among all routing algorithms, but also had the lowest success rate of data delivery. The Prophet Routing [13] selected the next hop based on the delivery possibility. If the delivery possibility of the relay node was higher than a threshold, the message would be forwarded to the relay node. The Prophet Routing dynamically updated the delivery possibility values of the links according to the historical information. The more frequently the nodes met, the higher the delivery possibility would be. If two nodes had not met each other for a long time, the delivery possibility to each other may decrease. In some scenarios, the Prophet Routing can have high delivery ratio and low overhead. There are other routing algorithms [14]–[16] which make the tradeoff between delivery success and network overhead, and have good performance in some specific scenarios. However, those traditional routing algorithms have a premise hypothesis which is all intermediate nodes in opportunistic networks should be willing to forward messages for other nodes. In real environment, the mobile devices acting as the nodes in opportunistic networks are belonging to different and independent owners. Due to the constrains of nodes’ capability, memory space, battery power and many other resources, the nodes may be inclined to behave selfishly. In epidemic routing, if all nodes is selfishness, the routing scheme will become direct transmission.

The problem of node selfishness in opportunistic networks has attracted the attention of many researchers recently. In [17], the authors explored the impact of node cooperation on some representative routing algorithms such as Epidemic, Two-Hop [18], Binary Spray and Wait [19], and so on. The authors proposed a simple incentive mechanism in which the cooperation degree was defined to improve the effectiveness of the three routing algorithms, and they found that the cooperation degree between nodes can affect the delivery ratio of network. In [5], the authors investigated how the selfish behavior of nodes affected the network performance. It demonstrated that the node selfishness had the delivery ratio decreased and the message transmission delay increased. It is widely agreed that the incentive to nodes is needed in opportunistic networks to overcome the free-riding problem, i.e., requesting others for forwarding its packets, but
There are three types of incentive mechanisms being studied, which are reputation, barter (or Tit-for-Tat), and virtual currency. In [20], the authors proposed an auction incentive mechanism using a fair pricing mechanism to incentive nodes, and modeled the pricing process as an auction game. This game can achieve a Bayesian Nash Equilibrium, in which the profit of each intermediate node can be maximized. In [21], [22], the authors proposed an incentive mechanism, called MuRIS, to allow nodes to cooperatively deliver information of interest to one another via chosen paths utilizing few transmissions. In [23], the authors proposed a multifunctional incentive scheme called Multi-centric, which was based on game theory, not only provided competitive incentive but also encouraged the nodes to follow defined rules to realize the desired performance objective. In [24], the authors proposed an incentive aware routing for selfish opportunistic networks from a game theoretic perspective, which jointly considered individual selfishness and social selfishness to improve the performance of opportunistic networks. The scheme mapped the message transmission between two nodes as a Rubinstein-Stahl bargaining game, which employed virtual currency and constructed a proper price function, while considering the nodes’ resources and social ties for data transmission. The drawback of this scheme is the higher energy and delay consumption in data transmission. In [25], the authors proposed a congestion-aware node cooperation mechanism based on double auction, in which the nodes determined the self congestion degree according to current free buffer and message receiving speed. Then, combining message delivery probability and congestion degree, the nodes traded messages based on double auction model. In [26], the authors proposed a routing protocol called SEIR, which was based on the Stackelberg Game theory model, and gave the intermediate node the best reward to eliminate the nodes’ selfishness. In [27], the authors proposed a Game based Incentive Strategy (GIS) which utilized three-time bargaining model based on two-person transaction and allowed the sending nodes to pay the intermediate nodes directly according to the optimal price drawn by game without any third party.

The above incentive mechanisms motivate the nodes to participate in message delivery. However, a node participating in message transmission has two stages which are first to receive messages from the source and then to opportunistically forward the messages to other nodes, if some nodes only receive messages, refuse to the long-term storage of the messages and forward the messages to others at last, it may cause the message losing. Since the above mechanisms are one-time incentive for message delivery, the nodes can not be maximally motivated to take part in message transmission, and two-stage incentive mechanism will be better to stimulate the selfish nodes and increase the success of message delivery. Based on the existing works, we design an incentive mechanism which applies the Game Theory [28] and Credit to improve the routing performance. In our mechanism, two-stage incentive is applied to message transmission, and each node can be encouraged to receive messages from the source nodes and forward the messages to others.

III. SYSTEM DESCRIPTION

We propose a Bertrand [30] Game-based Incentive mechanism (BGI) to motivate the selfish nodes to participate in message transmission in opportunistic networks. The BGI includes the definitions of the interactions between nodes, the reward mechanism of nodes participating in message transmission and the pricing mechanism. In this section, we present the details of interaction model between nodes in opportunity network. We consider the process of the message transmission is something like the transaction of the goods. It is assumed that the node carrying the message is the buyer in the market, and the source node purchases service from intermediate nodes for messaging delivery. The intermediate nodes are the sellers who sell the service of message transmitting to the source node, and they get reward from the source node. Obviously, the message transmission can seen as commodities in the market.

A. THE INTERACTION MODE

In an opportunistic network, it is supposed that the number of node is $n$, and the set of nodes is $N = \{1, 2, \ldots, i, \ldots, n\}$. A node may carry multiple messages, so that it may be not only the source node of a message, but also the destination node of another message, moreover it can act as a relay node in message transmission. But, a node can only forward a message for another node at a time. In our model shown in figure 1, the message sender is call the source node, and the nodes who are ready to receive and forward the message are called the relay nodes. Besides the source and relay nodes, there are many exchange points which can be integrated with base station, server and other fixed or mobile infrastructure. The nodes can get virtual currencies from the exchange points for their participating in message forwarding.

![Figure 1. The interaction between the source and relay nodes.](image-url)

In our model, the interaction between the source and the relay nodes have some steps. In the first step, the source broadcasts the request of message forwarding, and the nodes...
nearby the source are the candidate relay nodes, which receive the request and consider whether to forward messages for the source. In the second step, to the nodes who are ready to forward the messages, they respond to the source with their cost for forwarding a message, and different nodes may have different cost. In the third step, considering the cost of all relay nodes, the source reply to different nodes with different prices for forwarding a message, which should be the suitable prices for the relay nodes to receive and forward the messages. In the fourth step, considering the price given by the source, each relay node makes a decision of forwarding how many messages for the source, and responses the service plan to the source. At last, the source send the messages to the relay nodes according to the received service plan.

In order to encourage the cooperation between the nodes, both the source and the relay nodes will get rewards for their participating in message transmission. Since the source cannot complete the messages’ forwarding without the relay nodes receiving the messages, the relay nodes can get some rewards directly from the source for their receiving message. Therefore, the source will pay more if it forwards the messages to more relay nodes. But, the source can get rewards from the exchange points for their message forwarding, and more forwarding can have more rewards. The exchange points are distributed, and located anywhere integrated with other fixed or mobile devices. When the sources meet the exchange points, they will get virtual currencies from the exchange points for their finished tasks of forwarding messages.

In the one-hop transmission of message, there are two stages which are the message forwarding by the source and the message receiving by the relay node. In order to maximally encourage the participants, we have two-stage incentives for each node to take part in message transmission, that is, the nodes can get reward from both receiving and forwarding messages. To the source node, it can get the $c$ virtual currencies from the exchange points for the reward of forwarding a message. But, to the relay node, its reward for receiving a message directly comes from the source node. Moreover, the message forwarding can be validated by the exchange points according to the reports of the sender and receiver. Once a relay node received the messages, it would become the source node in next round and find some nodes to forward the messages referring to the above steps. The process repeats until the destination nodes receive the messages.

We model the interaction between the source and relay node as a commodity trading process and use game theory to find optimal price which stimulates more nodes to take part in message transmission for maximum utilities. To the source nodes acting as the buyer in the game, they expect the price of the commodity is as low as possible. However, as the service sellers, the relay nodes expect the higher price and sell more commodities, since they can get more reward. Therefore, for receiving a message, the higher price will lead to the less reward for the source node, but more reward for the relay nodes.

Before the further discussion of the nodes’ behavior, we present some assumptions. We assume that the exchange points are reliable, and can correctly evaluate whether the node forwards and receives the messages according to their reports. That is, the exchange points can never be cheated by the nodes. When the nodes are connected and share their service plans with the exchange points, the exchange points can accurately calculate their rewards, and they can surely get their rewards from the exchange points.

### B. THE UTILITY FUNCTIONS

From the interaction between the source and the relay node, we can know that the relay node will execute its service plan if the price given by the source is greater than its cost, and its service plan includes the number of messages which it wants to receive. To the source, it must take into account the cost of all relay nodes, and decide a reasonable price which can attract as many nodes as possible while ensuring its own reward. To the relay nodes, their utilities are affected by the number of messages which they decides to receive. But, the more the messages are received by a node, the greater the cost is. Therefore, the utility of the relay node will be saturated to a certain extent.

It is supposed that the relay node $j$ receives $a_i$ number of messages from the source node $i$, and the $a_i$ number of messages will be forwarded by node $j$ to other nodes in next round. Then, we define the utility function of relay node $j$ as equation equation (1), and the utility function of the source node $i$ as equation equation(2).

$$U_j = p_j a_i - c_j a_i - ba_i^2$$  \(1\)

In equation (1), $U_j$ is the utility of relay node $j$, $p_j$ is the price for the relay node $j$ to receive a message from the source node $i$, and $c_j$ represents the cost for the relay node to forward a message, and $b$ is the saturation coefficient.

$$P_j = a_i - p_j a_i$$  \(2\)

The utility of source node $i$ is the reward for forwarding messages to the relay node $j$, and the more messages are forwarded, the more utility will be. Therefore, the utility of source node is proportional to the number of messages forwarded. In equation (2), $c$ is system parameter given by exchange points and satisfying $c > p_j$, which means the price for any node to forwarding a message.

### C. THE REAL COST OF FORWARDING A MESSAGE

In the interaction between the source and relay nodes, the relay nodes must response to the source the cost of forwarding a message. In the long run, the relay nodes will feed back to the source node the real cost of forwarding a message. If the relay node $j$ gives the false cost to the source, the benefit of the relay node is not the best, as can be proved theoretically. We assume the relay node tell the source the false cost denoted as $c_j$, and the source response the price as $p_j’$. According to equation (1), its utility is $U_j’$ shown in
equation (3).
\[ U_j' = p_j' a_i - c_j a_i - ba_i^2 \] (3)

It is supposed the true cost is \( c_j \) for node \( j \) to forwarding a message, and corresponding the price and utility of node \( j \) are \( P_j \) and \( U_j \) respectively. Comparing \( U_j \) and \( U_j' \), we can get equation (4).
\[ U_j' - U_j = \left( \frac{c + c_j}{2} - c_j \right) \frac{e - c_j}{4b} \]
\[ -ba_i^2 - \left( \frac{c + c_j}{2} - c_j \right) \frac{e - c_j}{4b} - ba_i^2 \] (4)

According to arithmetic calculation, we can get \( U_j' - U_j \) as equation (5).
\[ U_j' - U_j = \frac{(c_j - c)^2}{8b} \] (5)

Since \( U_j' - U_j < 0 \), \( U_j' \) is less than \( U_j \). Therefore, it is the best strategy for the relay node to tell the source the true cost of forwarding a message.

IV. PRICING ANALYSIS BASED ON GAME THEORY

In our model, the nodes can get reward from the exchange points for their forwarding messages, which incentivizes the nodes to take part in message forwarding. In order to maximize the utility, the source should have the best pricing strategy, and the corresponding relay node should respond the best service plan. In this section, since the cooperation between the source and the relay node is similar to the interaction between the seller and buyer in Bertrand Game, the Bertrand game theory is used to analyze the interaction between the source and relay node.

In Bertrand Game, the source node is the buyer, since it has the messages to be sent, and it needs the forwarding service from the relay node. The relay node is the seller who provides the forwarding service to the source node. Obviously, the message forwarding is the commodity. If the demand of the commodities is given, the source node can calculate the most appropriate price based on the cost of relay nodes, so that the source node can get the maximum profit. If the price of the source node is lower than the cost of the relay node, the relay node will not forward the message for the source node. For the relay nodes, when the prices from all the source nodes are given, they will decide the number of messages forwarded for the source node to maximize their own profits. In the following, we will analyze the strategies of both sides, and show the Nash Equilibrium [28] of the game.

Based on the strategy of the source node, the relay node will develop a strategy which is the service plan to maximize its utility. The utility function of relay node \( j \) is equation (1), and we can get the first derivative of \( U_j \) as equation (6).
\[ \frac{\partial U_j}{\partial a_i} = p_j - c_j - 2ba_i \] (6)

The second derivative of \( U_j \) is equation (7).
\[ \frac{\partial^2 U_j}{\partial^2 a_i} = -2b \] (7)

Due to \( b > 0 \), the second derivative of \( U_j \) is negative. Therefore, \( U_j \) is strict convex function. Let the first derivative of \( U_j \) is equal to zero, we can get the maximum point of \( U_j \), and at that point \( a_i \) is shown in equation (8).
\[ a_i = \frac{p_j - c_j}{2b} \] (8)

As is shown above that when the strategy (price) of the source is given, the appropriate number of messages forwarded by the relay node is \( \frac{p_j - c_j}{2b} \), which will maximize the utility of the relay node.

Combining equation (8) and equation (2), we can get the utility of the source node showing as equation (9).
\[ P_j = e \frac{p_j - c_j}{2b} - p_j \frac{p_j - c_j}{2b} \] (9)

Then we can get the first derivative of \( P_j \) as equation (10).
\[ \frac{\partial P_j}{\partial p_j} = \frac{e - 2p_j + c_j}{2b} \] (10)

Then, the second derivative of \( P_j \) is as equation (11).
\[ \frac{\partial^2 P_j}{\partial^2 p_j} = -\frac{1}{b} \] (11)

Due to \( b > 0 \), the second derivative of \( P_j \) is negative. Therefore, \( P_j \) is strict convex function, and has the maximum point. Let the first derivative is equal to zero, we can get the best price \( p_j \) shown in equation (12), which will maximize the utility of the source node \( i \).
\[ p_j = \frac{c + c_j}{2} \] (12)

From the above analysis, the game between the source node \( i \) and relay node \( j \) will be in Nash Equilibrium at the point \( (c + c_j, p_j) \), which means the best strategy of the source node \( i \) is to give the relay to node \( j \) the price of \( \frac{c + c_j}{2} \), and the best strategy of the relay node \( j \) is to receive the number \( \frac{p_j - c_j}{2b} \) of messages from the source node \( i \).

V. SIMULATIONS

In order to verify the efficiency of the proposed incentive mechanism, simulation experiments were performed in ONE [31] simulator. In our simulation, the real datasets Infocom5, Infocom6 are used for node activity driving, which can be downloaded from CRAWDAD. Since we have the similar results in the mentioned datasets, only the results in Infocom5 and infocom6 are presented here, and the detailed information is shown in Table 1. In the simulations, each node is mobile with a speed in the range 0.5–1.5m/s. A message with the size of 500KB is generated after each 3000–4000 seconds. The shortest path map based movement model is considered, along with a terrain dimension of 4500 * 3400 square meters. System parameters \( c \) is 10,
and $b$ is $1/2$ and $3/2$ in Epidemic routing algorithm and Prophet routing algorithm, respectively. We find that the routing algorithms have the best performance with the above values of parameters, but we also have the analysis of the impact of parameter $b$ on routing performance.

### A. PERFORMANCE METRICS

In the experimental analysis, the delivery ratio, average delay and overhead ratio are used as the performance metrics, and they are defined as follows.

**Delivery Ratio:** The delivery ratio is defined as the ratio of the total number of messages successfully reached their destination\((success\_number)\) and the amount of total messages \((created\_number)\). The higher delivery ratio is, the greater the probability that the message will reach the destination node successfully. It can be shown as:

\[
delivery\_ratio = \frac{success\_number}{created\_number}
\]

**Overhead Ratio:** The overhead ratio is the ratio of the number of the failed forwarding messages and the number of packets successfully transferred to the destination, and the number of the failed forwarding messages is that the total number of packets to be forwarded \((forward\_number)\) minus the number of packets successfully transferred to the destination node \((delivered\_number)\). The lower the overhead, the better the performance. It is defined as:

\[
overhead\_ratio = \frac{forward\_number - delivered\_number}{delivered\_number}
\]

**Average Delay:** The average delay is defined as the average of the amount of time taken, from the time of creation of the message at the source node till the time of message arrived at the destination node, so a lower average delay was expected.

### B. SIMULATION SCENARIO

As we know, the existing routing algorithms are based on the cooperation among nodes. In this paper, we run Epidemic routing algorithm and Prophet algorithm to evaluate the performance of our proposed incentive mechanism by adjusting the number of the selfish nodes. Also, we assume that the selfish nodes are all profit-seeking, and they would be sure to cooperate with others if the rewards are higher than the cost. We consider the following six scenarios.

1. **Epidemic + No selfish node (E+N).** In the background of Epidemic routing algorithm, all nodes are willing to forward the message for other nodes without any incentives, and they can cooperate with each other. Since every node takes part in message transmission, the network performance in this scenario is the best. E+N is the benchmark for performance comparison.

2. **Epidemic + Selfish node (E+S).** In the background of Epidemic routing algorithm, we add selfish nodes to the network, and the selfish nodes will refuse to forward the messages in routing. Since the selfish nodes do not cooperate with others, the network performance is definitely negatively affected.

3. **Epidemic + Selfish node + BGI (E+S+BGI).** In the background of Epidemic routing algorithm, we add selfish nodes, and used the proposed BGI mechanism to stimulate the selfish nodes to cooperate with others. With the encourage of BGI, if there is a profit, the selfish nodes will forward the messages for others, and the network performance in this scenario will be better theoretically than (E+S).

4. **Epidemic + Selfish node + Reputation (E+S+R).** In the background of Epidemic routing algorithm, we will add selfish nodes, and reputation incentive mechanism is used, which is the difference with (E+S+BGI). We put emphasis on the comparison of E+S+BGI and E+S+R.

5. **Prophet + Selfish node + BGI (P+S+BGI).** Different with E+S+BGI, Prophet is used as the background routing algorithm. We want to show the performance of BGI in different routing algorithms.

6. **Prophet + Selfish node + Reputation (P+S+R).** Prophet is used for reputation incentive mechanism.

Theoretically, among the above six scenarios, since selfish nodes are not existed in E+N, the performance of E+N is the best, and the E+S may be the worst one due to no consideration of the incentive to selfish nodes. According to previous analysis, in the BGI, the reward of a node from forwarding message has the relation with the parameter $b$ in equation (7), and we can adjust the performance by changing the value of $b$. It should be noticed that in the BGI, all nodes are assumed to be selfish, and each node is stimulated to participate in message transmission by the incentive mechanism. Therefore, the number of selfish nodes has no relation with the performance of E+S+BGI.

### C. SIMULATION RESULTS ANALYSIS

As is shown in Figure 2, 3, 4 and 5, the delivery ratio drops sharply at the presence of selfish nodes without an incentive mechanism, since the selfish nodes do not participate in message transmission. The more selfish nodes, the lower the delivery ratio will be. If the number of selfish node is 0, which means that all node take part in message transmission, we can find all routing algorithms have almost the same performance as the normal Epidemic. When all nodes become selfish nodes, that is to say, none of the nodes is willing to help other node to forward the messages, the messages are transmitted only from the source node directly to the destination node, then Epidemic and Prophet are similar to the Direct Routing algorithm.

### TABLE 1. Simulation parameters of two experimental datasets in one.

| Dataset | Info/com5 | Info/com6 |
|---------|-----------|-----------|
| number of nodes | 41       | 98        |
| buffer size(M)   | 20       | 20        |
| TTL(hours)       | 5        | 5         |
| Simulation time(second) | 274883  | 342915    |
The simulation results show that selfish nodes seriously affect the transmission efficiency. If the proposed incentive mechanism is added, in order to maximize the profits, the selfish nodes consider the cooperation with others, so that the delivery ratio is greatly improved. Since no selfish node is considered in E+N, the performance of E+N is presented only the situation with zero number of selfish node. Since E+S+BGI takes all nodes as selfish nodes, E+S+BGI has the same performance under different number of selfish nodes.

From figure 2, 3, 4 and 5, we can see the proposed incentive mechanism has the highest delivery ratio when selfish node are existed in the network, and has almost the same delivery ratio as E+N, which shows the effectiveness of the incentive mechanism to selfish nodes. Compared with E+S+BGI has the delivery ratio increased by 22.9% in average. And, compared with P+S+BGI has the delivery ratio increased by 26.5% in average. When the routing algorithms are concerned, P+S+BGI has almost similar performance in Epidemic and Prophet.

With the increasing of the number of selfish nodes, the simulation results related to overhead are shown in Figure 6, 7, 8 and 9. Since selfish nodes do not participate in message forwarding, the overhead ratio in E+S and P+S decreases with the increasing of the number of selfish nodes. But, in E+S+BGI and P+S+BGI, the selfish nodes take part in message forwarding for maximize their profits, thus the overhead ratio will increase with more selfish nodes considered.

With the increasing of the number of selfish nodes, the average delay in different algorithms is shown in Figure 10, 11, 12 and 13. In opportunistic networks, the more nodes take part in message forwarding, the smaller delay is needed for message delivery from the source to the destination. From the simulation results, since our proposed mechanism can incentivise the selfish nodes to forward messages for others, it has smaller average delay than E+S and E+S+BGI. Compared with E+S and E+S+BGI, our proposed mechanism has the average delay decreased by 11.6% and 9.2% respectively. Compared with P+S and P+S+BGI, our proposed mechanism has the average delay decreased by
8.5% and 6.8% respectively. It must be noticed that with the BGI incentive mechanism, the average delay is almost the same as that of the E + N or P + N in which no selfish node is considered.

Since the nodes are rational, all nodes will participate in message transmission only for rewards. Consequently, each node wants to maximize their utility. But, each node should pay the cost for message receiving and forwarding, and with the given price of message transmission, each node has the optimal number of message forwarding. From the equation (7), the optimal number of message forwarding for each node can be adjusted by changing the value of parameter \(b\). If the optimal number of message is less than the number of messages which the source node wants to forward, some message will be rejected by the relay node to forward, thus the success rate of message transmission may decrease. In figure 14, 15 and 16, we present the simulation results to show the impact of parameter \(b\) on the performance of BGI.

From figure 14, 15 and 16, we can find that, with the parameter \(b\) given an appropriate value, the performance in E + S + BGI can be the same as that in E + N. In the above figures, message delivery ratio and overhead ratio decrease...
FIGURE 11. The impact of the number of selfish nodes on average ratio with Epidemic routing in Infocom6 dataset.

FIGURE 12. The impact of the number of selfish nodes on average ratio with Prophet routing in Infocom5 dataset.

FIGURE 13. The impact of the number of selfish nodes on average ratio with Prophet routing in Infocom6 dataset.

FIGURE 14. The impact of $b$ on average delay.

FIGURE 15. The impact of $b$ on delivery ratio.

FIGURE 16. The impact of $b$ on overhead ratio.

with the increasing of $b$, and average delay increases with the increasing of $b$. In our opinions, the smaller $b$ makes the nodes forward more messages, which will do good to message transmission, so that the delivery ratio increases and the average delay decreases. However, more message forwarding means the higher overhead done to the network. If $b$ is equal to 0.1, $E + S + BGI$ has the same delivery ratio and average delay with $E + N$, but higher overhead than that of $E + N$. When $b$ is less than 0.1, the performance has no changes, since each node forwards all messages for the others at that time.
VI. CONCLUSIONS

In this paper, we define the interaction steps between the source and the relay node, in which the source decides the price for the relay node to forward a message, and based on the given price, the relay node decides the number of the message to be forwarded. Since both the source and the relay node want to maximize their utilities, there exists a game between the two. Consequently, we model the cooperation between the source and the relay node as Bertrand Game, and propose an incentive mechanism to encourage the cooperation between nodes. In order to maximally encourage the participants, we provide two-stage incentives to each node for taking part in message transmission, that is, the nodes can get reward from both receiving and forwarding messages. To the source node, it can get reward from the exchange points for forwarding a message. To the relay node, its reward for receiving a message directly comes from the source node. We define the utility functions of the source and the relay node, and compute their best strategies. Based on game theory, we find that the Nash Equilibrium is existed and unique. The simulation results show that the proposed incentive mechanism can encourage the cooperation between selfish nodes, and improve the performance of routing algorithm in terms of delivery rate and delay. Compared with reputation-based incentive mechanism, the proposed mechanism BGI has better performance, and can encourage all nodes to participate in message transmission. With the parameter $b$ set a proper value, BGI used opportunistic network can has the same performance with the network in which selfish nodes are not considered.

REFERENCES

[1] R. Olaniyan, O. Fadahunsi, M. Maheswaran, and M. F. Zhani, “Opportunistic edge computing: Concepts, opportunities and research challenges,” Future Gener. Comput. Syst., vol. 89, pp. 653–645, Dec. 2018.

[2] P. Hui, J. Crowcroft, and E. Yoneki, “BUBBLE rap: Social-based forwarding in delay-tolerant networks,” IEEE Trans. Mobile Comput., vol. 10, no. 11, pp. 1576–1589, Nov. 2011.

[3] X. Zhu, Y. Luo, A. Liu, W. Tang, and M. Z. A. Bhuiyan, “A deep learning-based mobile crowdsensing scheme by predicting vehicle mobility,” IEEE Trans. Intell. Transp. Syst., early access, Oct. 7, 2020, doi: 10.1109/TITS.2020.3023446.

[4] M. Song, Z. Wang, Z. Zhang, Y. Song, Q. Wang, J. Ren, and H. Qi, “Analyzing user-level privacy attack against federated learning,” IEEE J. Sel. Areas Commun., vol. 38, no. 10, pp. 2430–2444, Oct. 2020.

[5] Y. Li, G. Su, D. O. Wu, D. Jin, L. Su, and L. Zeng, “The impact of node selfishness on multicasting in delay tolerant networks,” IEEE Trans. Veh. Technol., vol. 60, no. 5, pp. 2224–2238, May 2011.

[6] D. DeFigueiredo, B. Venkatachalam, and S. F. Wu, “Bounds on the performance of P2P networks using tit-for-tat strategies,” in Proc. 7th IEEE Int. Conf. Peer-to-Peer Comput. (P2P), Sep. 2007, pp. 11–18.

[7] M. Yu, A. Liu, N. N. Xiong, and T. Wang, “An intelligent game based offloading scheme for maximizing benefits of IoT-edge-cloud ecosystems,” IEEE Internet Things J., early access, Nov. 23, 2020, doi: 10.1109/JIOT.2020.3039828.

[8] O. Yan, A. Liu, N. Xiong, and T. Wang, “An effective early message is the source to join adaptive data aggregation scheme for sustainable IoT,” IEEE Trans. Netw. Sci. Eng., early access, Oct. 29, 2020, doi: 10.1109/TNSE.2020.3033938.

[9] S. Huang, Z. Zeng, K. Ota, M. Dong, T. Wang, and N. Xiong, “An intelligent collaboration trust interconnections system for mobile information control in ubiquitous 5G networks,” IEEE Trans. Netw. Sci. Eng., early access, Nov. 17, 2020, doi: 10.1109/TNSE.2020.3038454.

[10] S. Huang, A. Liu, S. Zhang, T. Wang, and N. Xiong, “BD-VTE: A novel bundle data based verifiable trust evaluation scheme for smart network systems,” IEEE Trans. Netw. Sci. Eng., early access, Aug. 7, 2020, doi: 10.1109/TNSE.2020.3014455.

[11] P. Mundur, M. Seligman, and G. Lee, “Epidemic routing with immunity in delay tolerant networks,” in Proc. IEEE Mil. Commun. Conf. (MILCOM), Nov. 2008, pp. 1–7.

[12] L. Wu, Y. Xia, Z. Wang, and H. Wang, “Be stable and fair: Random data scheduling for vehicular networks,” IEEE Access, vol. 6, pp. 32839–32849, 2018.

[13] T.-K. Huang, C.-K. Lee, and L.-J. Chen, “ProPHET+: An adaptive ProPHET-based routing protocol for opportunistic network,” in Proc. 24th IEEE Int. Conf. Adv. Inf. Netw. Appl., Apr. 2010, pp. 10–18.

[14] F. Zeng, N. Zhao, and W. Li, “Effective social relationship measurement and cluster based routing in mobile opportunistic networks,” Sensors, vol. 17, no. 5, pp. 1–19, 2017.

[15] F. Xia, J. Wang, X. Kong, D. Zhang, and Z. Wang, “Ranking station importance with human mobility patterns using subway network datasets,” IEEE Trans. Intell. Transp. Syst., vol. 21, no. 7, pp. 2840–2852, Jul. 2020.

[16] Y. Yan, Z. Chen, and J. Wu, “An effective data transmission algorithm based on social relationships in opportunistic mobile social networks,” Algorithms, vol. 11, no. 8, pp. 1–15, 2018.

[17] A. Panagakis, A. Vaios, and L. Stavrakakis, “On the effects of cooperation in DTNs,” in Proc. 2nd Int. Conf. Commun. Syst. Softw. Middleware, Jan. 2007, pp. 1–6.

[18] M. Grossglauser and D. N. C. Tse, “Mobility increases the capacity of ad hoc wireless networks,” IEEE/ACM Trans. Netw., vol. 10, no. 4, pp. 477–486, Aug. 2002.

[19] A. Li, W. Liu, S. Zhang, and M. Xie, “Fast multicast with adjusting transmission power and active slots in software define IoT,” IEEE Access, early access, Dec. 10, 2020, doi: 10.1109/ACCESS.2020.3043762.

[20] H. Zhou, X. Chen, S. He, J. Chen, and J. Wu, “DRAIM: A novel delay-constraint and reverse auction-based incentive mechanism for WiFi offloading,” IEEE J. Sel. Areas Commun., vol. 38, no. 4, pp. 711–722, Apr. 2020, doi: 10.1109/JSAC.2020.2971871.

[21] Y. Chen, S. He, F. Hou, Z. Shi, and J. Chen, “An efficient incentive mechanism for device-to-device multicast communication in cellular networks,” IEEE Trans. Wireless Commun., vol. 17, no. 12, pp. 7922–7935, Dec. 2018, doi: 10.1109/TWC.2018.2872981.

[22] Z. Zhang, S. He, J. Chen, and J. Zhang, “REAP: An efficient incentive mechanism for reconciling aggregation accuracy and individual privacy in crowdsensing,” IEEE Trans. Inf. Forensics Security, vol. 13, no. 12, pp. 2995–3007, Dec. 2018, doi: 10.1109/TIFS.2018.2834232.

[23] K. Chen, H. Shen, and L. Yan, “Multicent: A multifunctional incentive scheme adaptive to diverse performance objectives for DTN routing,” IEEE Trans. Parallel Distrib. Syst., vol. 26, no. 6, pp. 1643–1653, Jun. 2015.

[24] L. Li, Y. Qin, X. Zhong, and H. Chen, “An incentive aware routing for selfish opportunistic networks: A game theoretic approach,” in Proc. 8th Int. Conf. Wireless Commun. Signal Process. (WCSP), Oct. 2016, pp. 1–5.

[25] Q. Jiang, C. Men, Z. Tian, and M. Jia, “A congestion-aware node cooperation mechanism based on double auction for opportunistic networks,” Int. J. Future Gener. Comput. Netw., vol. 9, pp. 105–122, Oct. 2016.

[26] X. Liu, H. Song, and A. Liu, “Intelligent UAVs trajectory optimization from space-time for data collection in social networks,” IEEE Trans. Netw. Sci. Eng., vol. 2, no. 4, pp. 32839–32849, 2018.

[27] Y. Chen, S. He, F. Hou, Z. Shi, and J. Chen, “An efficient incentive mechanism for device-to-device multicast communication in cellular networks,” IEEE Trans. Wireless Commun., vol. 17, no. 12, pp. 7922–7935, Dec. 2018, doi: 10.1109/TWC.2018.2872981.
QINGHUA LI received the Ph.D. degree from the School of Information Science and Engineering, Central South University, Changsha, China, in 2010. He has been working as an Associate Professor with Lingnan Normal University, Zhanjiang, China, since 2018. His research interests include wireless networks, network quality of service, edge computing, and big data.

FENG ZENG (Member, IEEE) received the B.Eng. and M.Eng. degrees in computer science from Hunan University, in 2000 and 2005, respectively, and the Ph.D. degree in computer science from Central South University, in 2010. He is currently an Associate Professor with the School of Computer Science and Engineering, Central South University. His current research interests include wireless networks, crowdsourcing, and opportunistic routing.

QING WU was born in Changsha, Hunan, China, in 1994. She received the B.Eng. degree in software engineering from Changsha University, Changsha, China, in 2017. She is currently pursuing the M.Eng. degree in software engineering with Central South University, Changsha, Hunan, China. Her research interests include wireless networks and game theory.

JUNJIE YANG received the Ph.D. degree from the Huazhong University of Science and Technology, Wuhan, China, in 2006. He has been working as a Professor with Lingnan Normal University, Zhanjiang, China, since 2009. His research interests include computer networks, optimization, and data mining with their applications.