A Game Theoretic Routing Protocol for 3D Underwater Acoustic Sensor Networks

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***Abstract*—As a key technology of Internet of Underwater Things (IoUT), underwater acoustic sensor networks (UASNs) have attracted considerable attentions from both academia and industry. Due to specific characteristics of UWSNs, such as high latency, high mobility and low bandwidth, it is challenging to design routing protocols for three-dimensional (3D) UASNs. In order to address these challenges, here we propose a game theoretic routing protocol (GTRP) for 3D UASNs. Firstly, the GTRP defines a forwarding area making the nodes closer to the destination inclined to forward. Then, it estimates the node degree in the forwarding area without broadcasting prior message periodically. Thirdly, GTRP regards the forwarding process as a game. The number of participants in the game is the node degree information in the forwarding area, instead of the number of actual neighbors. To test the effectiveness of the proposed GTRP, we implement it and evaluate its performance in the Aqua-sim. The extensive simulations results indicate that GTRP significantly outperforms some existing protocols used for comparison, in terms of the number of received packets, the packet delivery fraction, and the end-to-end delay.**

***Index Terms*—Internet of Underwater Things, Underwater Acoustic Sensor Networks, Game Theoretic, Routing Protocol, Node Degree**

I. Introduction

THE Internet of Things (IoT) can connect to ubiquitous devices and facilities, and can provide efficient and secure services along with various networks for real applications in the oceans [1][2][3]. Driven by the development of the terrestrial IoT, the Internet of Underwater Things (IoUT) was proposed since 2010s. It is defined as a world-wide network of smart interconnected underwater objects that enables to monitor vast unexplored water areas [4]. IoUT has broad application prospects in the civil and military fields, such as environmental monitoring, military defense, marine resources exploring, disaster prevention, assisted navigation, etc. [5].

As a key enabling technology of IoUT, underwater acoustic sensor networks (UASNs) has appeared to be a promising method for observing underwater environments. Radio waves have been widely used as wireless transmission media in terrestrial sensor networks, while it does not perform well in underwater environments due to the significant attenuation. In addition, light waves can be highly scattered underwater, making them inapplicable for long range signal transmission. Finally, the acoustic waves are considered as the feasible medium which is able to achieve good performance for long range transmission in underwater environments.

However, the transmission based on acoustic waves in underwater suffers from high propagation delay, high attenuation, multipath, Doppler effect, small bandwidth, and high-energy consumption [6][7]. In addition, problems can come from the continuous movement of sensor nodes as the water flow, inapplicability of global positioning system (GPS) and complexity of the underwater three-dimensional (3D) nature environment. Due to these problems, the routing protocol for the terrestrial wireless networks cannot be used in underwater directly. Therefore, adaptive, scalable, and efficient routing protocols are needed for UASNs.

The decision-making of the forwarding nodes seriously affects the overall performance of routing protocols, which can be optimized by game theory. Game theory has comprised a powerful set of techniques to reason about situations involving conflict and competition [8]. It has a powerful analytical capability for implementing efficient routing protocols for ad hoc networks and opportunistic networks [9][10]. Motivated by the above considerations, we propose a game theoretic routing protocol (GTRP) for 3D UASNs in this paper. It applies a game theoretic method on 3D UASNs routing protocol design for the first time. The main contributions of the GTRP are as follows.

1) GTRP defines a novel forwarding area for 3D UASNs. The forwarding area determines whether the node participates in forwarding or not, which affects the performance of the

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routing protocol. Through the design of the forwarding area, GTRP makes the nodes closer to the destination inclined to forward, which is the key to success for the proposed protocol.

2) GTRP designs a novel scheme to estimate node degree in the forwarding area for 3D UASNs. GTRP assumes that the location of nodes in 3D UASNs is subject to uniform distribution, and then estimates the node degree. Compared with broadcasting prior message, e.g., 'Hello', periodically to obtain the node degree, GTRP avoids unnecessary overhead.
3) GTRP designs a novel game theoretic based forwarding strategy for 3D UASNs. It regards the forwarding process as a game. The number of participants in the game is the node degree information in the forwarding area, instead of the number of actual neighbors. It designs strategy sets and gain function, and then obtains the forwarding probability by Nash equilibrium.

The rest of this paper is organized as follows. Section II introduces the related previous works. GTRP protocol and its implementation process are described in Section III. Section IV verifies the performance of GTRP using Aqua-sim. Section V concludes the paper and follows future work.

II. Related work

In recent decades, several typical routing protocols for 3D UASNs have been proposed, which can be classified into location-based and location-free routing [6]. Localization-free routing protocols are also termed as flooding based schemes, where nodes are only aware about their depth. On the other hand, location-based routing protocols assume that the sensor nodes are location aware.

Depth based routing protocol is an important location-free routing protocol for 3D UASNs. In [11], a location-free depth based routing (DBR) protocol was proposed. DBR obtains the depth information by a pressure sensor, and forwards packets to the shallower nodes greedily until to the sink on the water surface. However, in some scenarios, such as a sparsely deployed network, DBR cannot find the eligible next hop when a void hole occurs. To address the void region and detouring forwarding of DBR, a distance vector based opportunistic routing (DVOR) was proposed [12]. DVOR uses the query mechanism to establish the distance vector toward the destination nodes for each node, and then forwards the packets to the destination hop-by-hop along the opportunistic shortest path. In order to reduce the probability of encountering void holes in the sparse networks, a weighting depth and forwarding area division DBR routing (WDFAD-DBR) was presented [13]. The WDFAD-DBR considers not only the current depth but also the depth of expected next hop to decide the next hop forwarding nodes. By doing in this way, the WDFAD-DBR decreases the probability of meeting void holes.

Energy efficiency has been a major design concern for 3D UASNs. In [5], an energy-efficient depth-based routing protocol (EEDBR) was proposed. The EEDBR utilizes the depth and the residual energy of sensor nodes as a routing selection metric. Compared to the DBR, the EEDBR performs better in terms of network lifetime, energy consumption and the end-to-end delay. To further enhance the energy efficiency, an improved adaptive mobility of courier nodes in threshold-optimized depth-based-routing (iAMCTD) was implemented [14]. Different from existing depth-based routing protocols, the iAMCTD exploits network density for time-critical applications. It calculates optimal holding time and uses the signal-to-noise ratio, signal quality index, energy cost function (ECF), and depth-dependent function as routing selection metrics. In [15], a tailored delay-aware energy-efficient routing protocol (DEEP) was proposed. The DEEP involves an adaptable forwarding node selection mechanism, which incorporates energy efficiency and further reduces the collision rate. In order to address the energy consumption problem, an energy efficient cooperative opportunistic routing (EECOR) protocol was proposed [16]. The EECOR let the source nodes determine a forwarding relay set based on the local information of the forwarder. Then, it applies a fuzzy logic-based relay selection scheme to select the best relay.

In order to adapt to the dynamic environment of 3D UASNs, several routing protocols based on Q-learning techniques have been proposed. In [17], a Q-learning based routing algorithm called QELAR was implemented to optimize a total energy consumption and network lifetime. It estimates the Q-value by considering the energy consumption of sensor nodes and residual energy distribution among neighboring nodes. Similar to QELAR, QKS was also based on Q-learning with additional kinematic and sweeping features [18]. It demonstrates faster convergence and better estimates of dynamic networks than the baseline algorithm QELAR.

Pressure based routing protocol is another important location-free routing protocol for 3D UASNs. HydroCast, a hydraulic pressure-based routing protocol was presented in [19]. It uses anycast routing by exploiting the measured pressure levels in order to forward the data packets towards surface buoys. To reduce the probability of encountering void holes, a void-aware pressure routing (VAPR) protocol was proposed [20]. It detects the void nodes by periodic beacons, and then changes the forwarding direction to recover routing. Using this trail, opportunistic directional forwarding can be efficiently performed even in the presence of voids.

This serious shortcoming of location-free routing for 3D UASNs is inherently due to the nodes' blindness to the network topology, as they make localized routing decisions [21]. In the location-based routing, it is assumed that each node knows geographical information about itself. Therefore, each node has global view of the network topology, with which packets can always be routed efficiently. The vector-based forwarding (VBF) [22] uses the position information of source, sink, and intermediate forwarders to calculate a "routing pipe". The packets are forwarded through this pipe from the source to the destination. Only the nodes in this pipe are eligible for forwarding. By doing so in this way, the VBF not only reduces the network traffic, but also manages the dynamic topography. However, the performance of VBF is significantly affected by the constant routing pipe radius threshold. On the other hand, if the void hole occurs, the VBF may not be able to find the forwarding nodes, especially in the sparse networks. In order to increase the robustness of VBF, an enhanced version of VBF called hop-by-hop vector-based forwarding (HH-VBF) has been proposed [23]. It adopts the same idea of routing pipe as that used by the VBF. Instead of using a single pipe from source to destination, HH-VBF defines per hop routing pipe for each forwarder. In this way, every node participating in forwarding makes decision on the pipe direction according to its current location information. The HH-VBF performs better than the VBF for packet delivery fraction especially in sparse areas, but its constant routing pipe radius threshold still affects its performance seriously. To reduce the influence of constant routing pipe radius threshold on the performance of HH-VBF and VBF, an adaptive hop-by-hop vector-based forwarding routing protocol called AHH-VBF was proposed [24]. The AHH-VBF changes the routing pipe radius threshold hop by hop to restrict the forwarding range, while guarantees transmission reliability effectively in the sparse sensor region and reduced the duplicated packets in the dense sensor region.

The performance of above location-based routing protocols is directly dependent on the radius of virtual pipeline. However, the main challenges in these protocols are to find the optimum radius, which varies for different scenarios and would require repeated simulations for all possible scenarios. Therefore, it is impractical to identify a single optimum value for radius.

Our approach in this paper falls into optimizing forwarding process of routing protocols for 3D UASNs by applying game theory. Game theory has been used to model forwarding process for Ad Hoc networks and opportunistic networks. In [25], AODV+FDG has been proposed based on game theory. It adopted forwarding dilemma game (FDG) for broadcasting the flooding packets in Ad Hoc networks. However, it consumes a large amount of node's energy by broadcasting hello messages periodically to obtain one-hop node degree information. To reduce the influence of hello messages, a node degree estimation and static game forwarding based routing protocol (NGRP) for Ad Hoc networks is proposed [26]. It adopted game theory to improve forwarding efficiency, and considered impact of network boundaries to calculate the number of participants in the game without broadcasting hello messages. In [27], a game theoretic model was used to identify optimal network paths. A game theoretic approach for context based routing (GT-ACR) for opportunistic networks was implemented [9]. It uses game theory for selecting the best possible next-hop to forward data packets efficiently. However, the above mentioned game theory based routings were proposed for 2D networks, and used the radio waves as wireless transmission media. Therefore, they were not suitable for 3D UASNs. In this paper, we propose a game theoretic routing protocol named GTRP for 3D UASNs. It regards the forwarding process as a game for 3D UASNs for the first time. The GTRP defines a new forwarding area, and designs a novel scheme to estimate node degree, then designs a novel game theoretic based forwarding strategy.

III. PROPOSED APPROACH

A. *Network Architecture*

The GTRP adopts a network architecture as depicted in Fig. 1. The black dots represent the underwater sensor nodes, while the yellow balls represent their communication range. There are one destination node, one source node and some forwarding nodes in 3D UASNs. The source node is positioned at the sea floor, while the destination node is at the sea surface, thus their effective communication range is half of the yellow ball. Underwater sensor nodes are deployed to collect information data sensed from the surrounding region and send the data to the destination node. The destination node is equipped with both acoustic modems and radio modems. The destination node uses acoustic links for underwater communications, while radio links are for air and land communications. The source node collects the information from the sea floor, and then sends the packets to its neighbor nodes. When the intermediate underwater sensor nodes receive the data packets, they send them to their neighbor hop by hop, until the data arrives at the destination node. Then, the destination node forwards the received packets to satellites, unmanned aerial vehicle, or other onshore base stations over radio wireless channels.

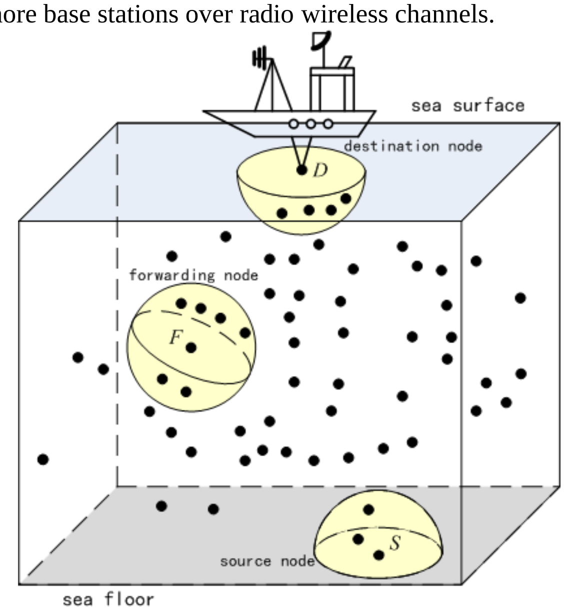

Fig. 1 Network architecture.

B. *Network Model of the GTRP*

Fig. 2 illustrates the basic idea of GTRP and the terminologies, where *D* is the destination node and its location information is (x_D, y_D, z_D), *F* is the forwarding node, and *I*, *B* and *C* are the neighbor nodes of *F*. *R* is the radius of each node. d_{IF} is the distance between the node *I* and the node *F*. θ_{IFD} is the angle between the vectors $\overrightarrow{FI}$ and $\overrightarrow{FD}$. ΔIFD represents triangle *IFD*. The shaded area is perpendicular to $\overrightarrow{FD}$. The communication range of each node is calculated as follows:

$$S = \frac{4}{3}\pi R^3 \tag{1}$$

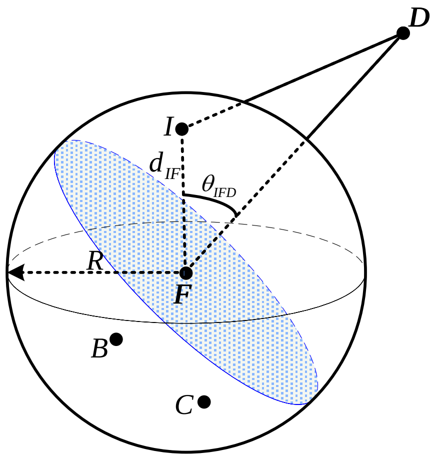

Fig. 2. Network model of the GTRP

C. Forwarding Area of GTRP

The GTRP defines the forwarding area criterion to avoid the unnecessary forwarding. When a node receives a packet, it first computes its forwarding area criterion and determines if it is in the forwarding area of the last hop neighbor node. Fig. 2 illustrates the forwarding area of node *F*. The general principle of the proposed scheme is shown in Fig. 3

The y-axis represents the Euclidean distance d between two nodes: the receiver node and the last hop node. The x-axis represents the angle between the vectors $\overrightarrow{FI}$ and $\overrightarrow{FD}$. This forwarding area has two parts, as shown in the Fig. 4. Taking as an example, the shaded area is the boundary between the forwarding zone and the no forwarding zone. The nodes above the boundary are encouraged to participate in forwarding, which means that the nodes closer to the destination are entitled to participate in forwarding. Therefore, only the node *I* is in the forwarding zone.

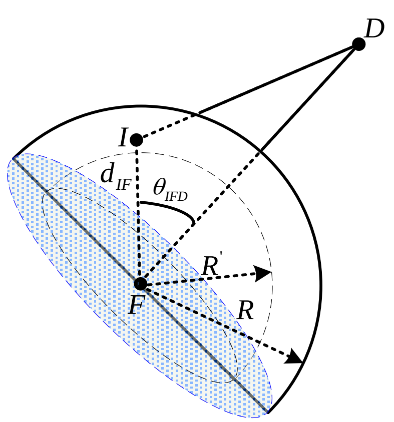

Fig. 3. Forwarding area schematic

The forwarding area of node *F* is expressed as:

$$F(\theta_{IFD}, d_{IF}) = \left\{ (\theta_{IFD}, d_{IF}) \middle| \begin{matrix} \theta_{IFD} \in [0, \frac{\pi}{2}] \cup [\frac{3\pi}{2}, 2\pi] \\ d_{IF} \in [R', R] \end{matrix} \right\} \quad (2)$$

where $R' = \alpha R \ (0 < \alpha < 1)$, the distance d_{IF} between *I* and *F* is given by:

$$d_{IF} = \sqrt{(x_I - x_F)^2 + (y_I - y_F)^2 + (z_I - z_F)^2} \quad (3)$$

Similarly, the d_{DF} and d_{DI} can be obtained.

In ΔIFD , according to cosine theorem, we obtain

$$\cos\theta_{IFD} = \frac{d_{IF}^2 + d_{FD}^2 - d_{ID}^2}{2d_{IF} \times d_{FD}} \quad (4)$$

because $\theta_{IFD} \in [0, \frac{\pi}{2}] \cup [\frac{3\pi}{2}, 2\pi]$, $0 \le \cos\theta_{IFD} \le 1$. The forwarding area of the node *F* is then expressed as:

$$F(\cos\theta_{IFD}, d_{IF}) = \left\{ (\cos\theta_{IFD}, d_{IF}) \middle| \begin{matrix} \cos\theta_{IFD} \in [0,1] \\ d_{IF} \in [R', R] \end{matrix} \right\} \quad (5)$$

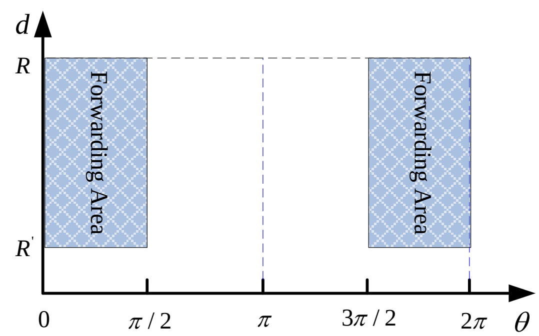

Fig. 4. Forwarding area

D. Node Degree Estimation of the GTRP

The total 3D area of an UASNs network is $L \times W \times H$, where L , W and H represent the length, width and height of the network scene, respectively, and n represents the total number of nodes in the entire network. The nodes' geographical location is uniformly distributed. The communication range of the forwarding area is given by

$$V_F = \frac{2}{3}\pi R^3 - \frac{2}{3}\pi R'^3 = \frac{2}{3}\pi R^3 (1 - \alpha^3) \quad (6)$$

The node degree in the forwarding area is estimated by

$$N_F = \frac{(n-1)V_F}{LWH} = \frac{2(n-1)\pi R^3 (1-\alpha^3)}{3LWH} \quad (7)$$

E. Game Forwarding Strategy of GTRP

The GTRP regards the forwarding process as a game theoretic process, that is to say nodes participating in the forwarding do not know the strategies of other nodes when they make decisions. There is no exchange of game information among nodes who participate in forwarding. Once nodes make decisions, the development of game will not be affected. Game theoretic forwarding is defined as below:

$$G = \{N_F, A, U\} \tag{8}$$

where N_F denotes node degree in forwarding in the forwarding area, and its quantity is computed by Eq. (7); A denotes a strategy set which contains forwarding element and non-forwarding element; U denotes a utility function, as shown in TABLE I.

TABLE I
FORWARDING DILEMMA GAME

$N_O - 1$ \ Other	**All nodes do not forward packets**	**At least one node forwards packets**
Non-forwarding	**0**	u
forwarding	$u-v$	$u-v$

In TABLE I, $u \geq v > 0$. It is shown that any node in the forwarding area is selected as the current node to make analysis, when N_F nodes are used as the participants of forwarding game. When both the current node and other $N_F - 1$ nodes do not forward packets, the benefit is 0; when the current node does not forward packets and at least one of other nodes $N_F - 1$ does, the benefit is u; when the current node forwards packets and other $N_F - 1$ nodes do not, the benefit is $u-v$; when both the current node and other $N_F - 1$ nodes forward packets, the benefit is still $u-v$. It is assumed that all nodes in game forward packets in a fixed probability P, and then the probability that at least one node among other $N_F - 1$ nodes forwards packets is:

$$P_{N_F - 1} = 1 - (1-P)^{N_F - 1} \tag{9}$$

The Nash equilibrium point of game theoretic forwarding is as following: the benefit of current node forwarding the packets equals to the benefit when at least one node among other $N_F - 1$ nodes forwards packets, which is expressed as

$$u - v = u \times P_{N_F - 1} \tag{10}$$

Let $u = \beta v$, β is a constant and $\beta > 1$. By substituting it into Eq.(10), we obtain

$$P = 1 - (\beta)^{-\frac{1}{N_F - 1}} \tag{11}$$

If $N_F = 1$, we set $P = 1$. Combining Eq. (7), we can obtain

$$P = 1 - (\beta)^{-\frac{3LWH}{2(n-1)\pi R^3 (1-\alpha^3) - 3LWH}} \tag{12}$$

F. Forwarding Process of the GTRP

In the GTRP, each packet carries the positions of the target and the forwarder. Consider a node n_i which receives a packet for the first time from the source or a forwarder node n_j. The packet carries the positions of destination node D and **forwarder** node n_j. If n_i is not the destination and it is in the forwarding area of n_j, it calculates the forwarding probability P by Eq. (12), and then rebroadcasts the received packet with forwarding probability P. Else, n_i discards the packet. The procedure of the forwarding function is shown in TABLE II.

TABLE II
THE PROCEDURE of FORWARDING FUNCTION

GTRP forwarding ()
Definitions:
n_i : Intermediate node.
n_j : Last hop node of n_i.
$FA(n_j)$: Forwarding area of n_j
P : Forwarding probability.
RN : A random number between [0, 1).
$N_F(n_j)$: Node degree of n_j in forwarding area.

1. If n_i receives a packet form n_j for the first time.
2. **If** n_i is not the destination node.
3. **If** $n_i \in FA(n_j)$
4. n_i calculates P by (12).
5. Generating the RN.
6. **If** $RN \leq P$
7. n_i rebroadcasts the packet.
8. **Else**
9. n_i discards the packet.
10. **Else**
11. n_i discards the packet.
12. **Else**
13. n_i receives the packet as the destination.

IV. PERFORMANCE EVALUATION

A. Simulation Environment

We use Aqua-sim [28], which is an NS-2 [29] based simulator for underwater sensor networks simulation, to evaluate the performance of the GTRP compared to the VBF and the HH-VBF. In the simulation, we deploy the nodes in the region of 500m×500m×500m. The nodes are uniformly distributed in the region. There are one data source and one destination. The initial position of the source node is (100, 300, 0), while the destination node is fixed at (250, 250, 500). The radius of the routing pipe of the VBF and the HH-VBF is 75m. The energy consumptions in sending mode, receiving mode and idle mode are 2w, 0.75w and 8mw respectively. The simulation time for all scenarios is 500s. The transmission range is set to 100 meters. The initial energy of nodes is 200J. Each data point represents an average of thirty runs with identical traffic models, but different seed from 1 to 30. For the sake of simplicity, TABLE III summarizes the global simulation parameters.

TABLE III
SIMULATION PARAMETERS

Name	Description
Routing protocols	GTRP, HH-VBF, VBF
Simulation time	500s
Transmission range	100m
Queue length	50
Propagation model	Underwater Propagation

Antenna	OmniAntenna
MAC	UnderwaterMac/BroadcastMac
PHY	UnderwaterPhy
Channel	Underwater Channel
Initial energy	200 J
Transmission power	2.0 W
Receiving power	0.75 W
Idle power	0.008 W
Min Speed	0.2m/s
β	10^6

B. Performance Metrics

To prove the effectiveness of the proposed approach, we use five metrics: (1) Number of Received Packets is defined as the number of packets successfully received by the destination; (2) Packet Delivery Fraction (PDF) is defined as the ratio of the number of packets successfully received by the destination to the number of packets generated by the source; (3) End-to-End Delay is the average time for data packets to reach the destination; (4) Average Energy Consumption is defined as the total energy consumption divided by the number of received packets; (5) Average collisions is the total number of collisions divided by the number of received packets.

C. Effects of α on the GTRP

The purpose of the simulations presented in this subsection is to investigate the effects of α on the performance of GTRP. We tune α from 0.1 to 0.9 in order to reach an optimized behavior.

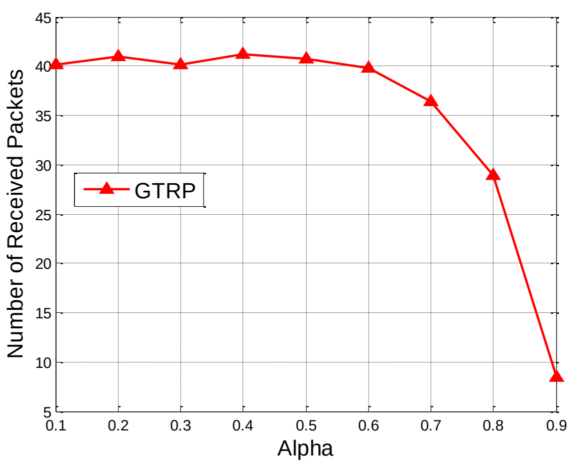

Fig. 5. Number of Received Packets

Fig. 5 shows the effects of α on the number of received packets. It is clear that when $0.1 \le \alpha \le 0.5$, the number of received packets of the GTRP keeps stable with the increase of α. It is due to the fact that with the increase of α, the forwarding area of nodes decreases, making the number of node participate in forwarding decreases. Nevertheless, there are still enough nodes in the forwarding area, thus the number of received packets is stable. When $0.5 < \alpha \le 0.9$, the number of received packets of GTRP decreases seriously with the increase of α. Because of this, the forwarding area of node reduces rapidly, and the number of nodes participating in forwarding is insufficient. Fig. 6 depicts the relationship between packet delivery ratio and α. It is seen that the packet delivery ratio of the GTRP shows the same trend as that shown in Fig. 5.

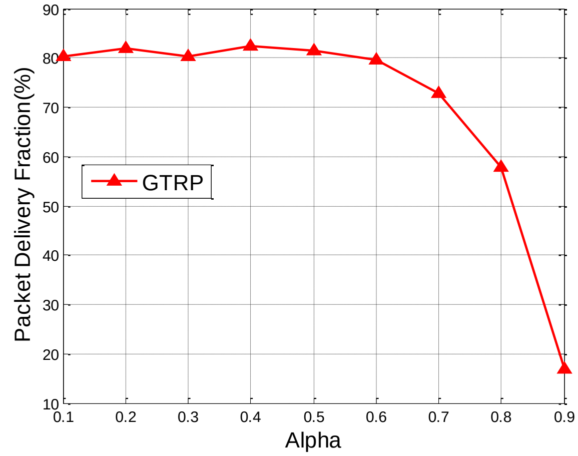

Fig. 6. Packet delivery ratio

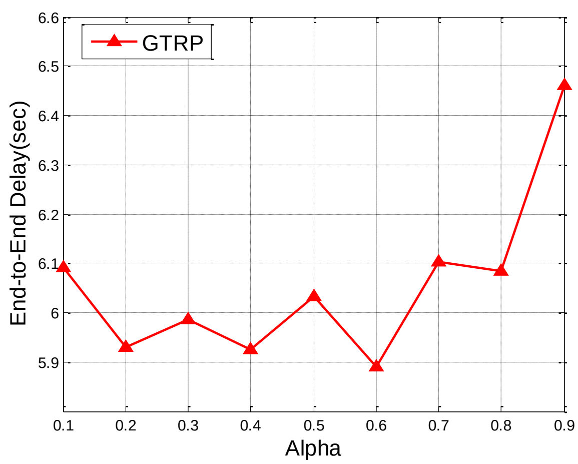

Fig. 7. End-to-End Delay

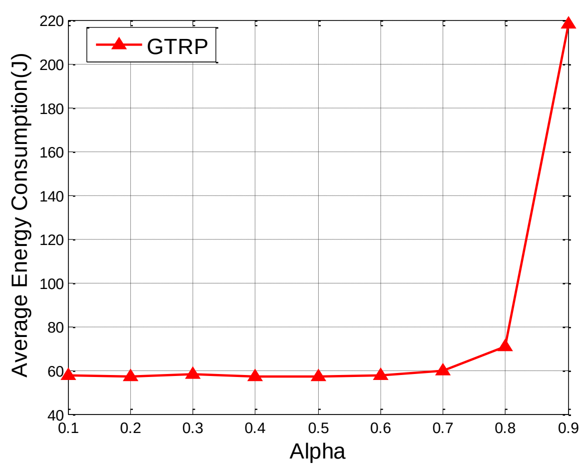

Fig. 8. Average Energy Consumption

Fig. 7 illustrates the effects of α on the average end-to-end. It is clear that when $\alpha \le 0.8$, the overall trend of end-to-end delay is stable except a little fluctuation. When $\alpha > 0.8$, the end-to-end delay of GTRP increases quickly. The reason is that when $\alpha \leq 0.8$, the number of packets by destination node decreases rapidly. Fig. 8 illustrates the effects of α on average energy consumption. It is observed that when $0.1 \leq \alpha \leq 0.8$, the average energy consumption of the GTRP keeps stable with the increase of α. When $\alpha > 0.8$, the average energy consumption increases quickly. The reason is that when $\alpha \leq 0.8$, the destination node receives very few packets.

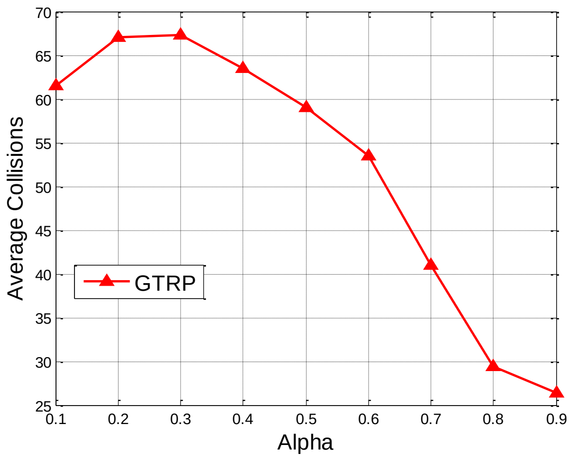

Fig. 9. Average Energy Collisions

Fig. 9 illustrates the effects of α on average collisions. It is observed that when $0.1 \leq \alpha \leq 0.3$, the average collisions increases with the increase of α. When $\alpha > 0.3$, the average collisions decrease with the increase of α. The reason is that when $\alpha > 0.3$, the number of nodes participating in forwarding decrease gradually.

Considering the effect of α on the above five metrics, we choose $\alpha = 0.1$ for the next section simulations.

D. *Effects of the Node Density*

The purpose of the simulations presented in this subsection is to investigate the effects of different network density on the performance of these protocols. The number of nodes changes between 200 and 400. The maximum speed is 3 m/s. The minimum speed is 0.2 m/s.

Fig. 10 presents the effects of the network density on the number of received packets. As can be seen, the metric is increased as the network density grows. The GTRP performs better than the HH-VBF and the VBF. The reason is that the GTRP adopts forwarding area and the forwarding probability, letting the nodes closer to the destination inclined to forward. Thus, the number of the packets reaching the destination is increased. Fig. 11 depicts the relationship between packet delivery fraction and network node density. It is seen that the packet delivery ratio of the GTRP is obviously better than the HH-VBF and the VBF. The metric of three protocols shows an increase tendency with the increase of node density. The reason is that the GTRP adopts forwarding area and game forwarding strategy to let the nodes closer to the destination inclined to forward, which improves the efficiency of forwarding packets.

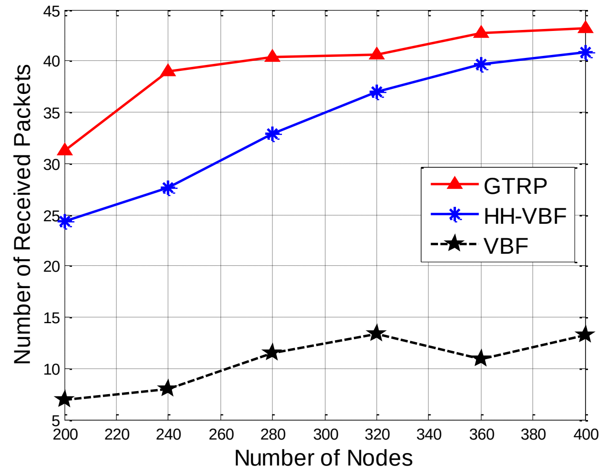

Fig. 10. Number of Received Packets

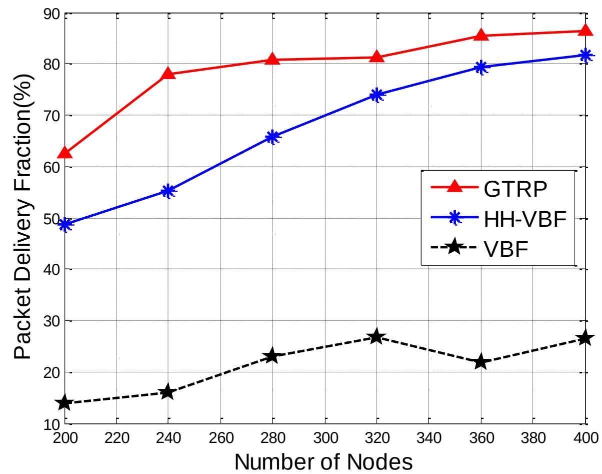

Fig. 11. Packet Delivery Fraction

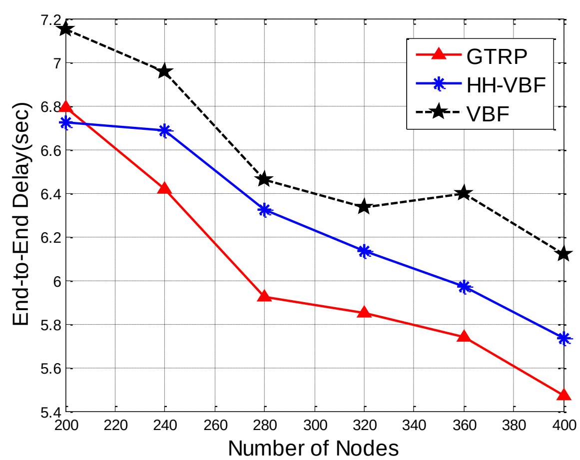

Fig. 12. End-to-End Delay

Fig. 12 examines the effects of the network density on the average end-to-end delay. It is clear that with the increase of node density, the end-to-end delays of the three protocols decreases gradually. The average end-to-end delays of GTRP are obviously better than the HH-VBF and the VBF. It is due to the fact that with the increase of node density, the GTRP let the nodes in the forwarding area participate in forwarding.

Therefore, it is not affected by the radius of virtual pipeline similar to HH-VBF and VBF. Thus, the number of the packets received by the destination is increased, the average end-to-end delay decreases accordingly. Fig. 13 illustrates the results of average energy consumption vs. the network density. As shown in the figure, the metric of GTRP is close to that of HH-VBF and much better than that of VBF. The reason is that GTRP let the nodes closer to the destination forward the received packets hop by hop, so more packets reach the destination.

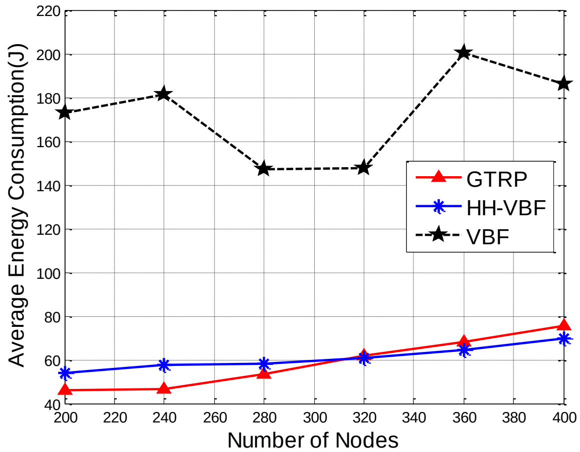

Fig. 13. Average Energy Consumption

Fig. 14 depicts the relationship between average collisions and network node density. It is clear that with the increase of node density, the average collisions of the three protocols increases gradually. The HH-VBF and the VBF perform better than the GTRP. This is because the HH-VBF and the VBF forward a lower number of packets, which decreases the collision probability.

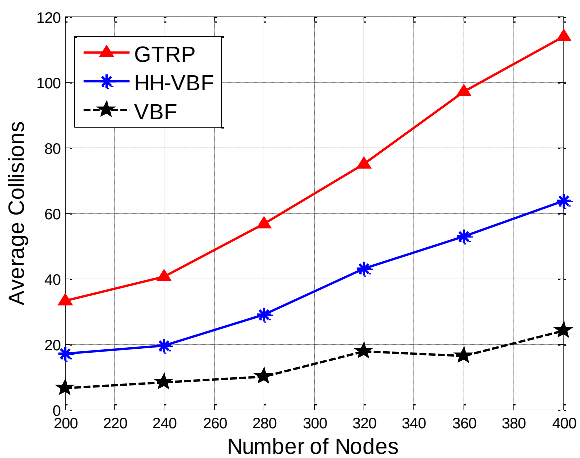

Fig. 14. Average Collisions

E. *Effects of the Node' Maximum Speed*

The purpose of the simulations presented in this subsection is to study the effects of the nodes' maximum speed on the performance of these protocols. The nodes' maximum speed changes between 2 m/s and 20 m/s. The value of the nodes' minimum speed is 0.2 m/s, and the number of nodes is 300.

Fig. 15 presents the effects of the nodes' maximum speed on the number of received packets. It is obvious that the GTRP has better performance than the HH-VBF and the VBF. When the maximum speed is less than 8 m/s, the performance of GTRP and HH-VBF increases slightly. The performance of GTRP and HH-VBF protocols keeps stable when the maximum speed of nodes is greater than 8 m/s and less than 20 m/s. The performance of VBF remains stable with the increase of nodes' maximum speeds. The reason is explained as follows. GTRP adopts forwarding area and the forwarding probability, thus let the nodes closer to the destination forward, which increases the number of the packets reaching the destination. Fig. 16 depicts the relationship between nodes' maximum speed and packet delivery fraction. It is seen that the packet delivery ratio shows the same trend as that shown in Fig. 15.

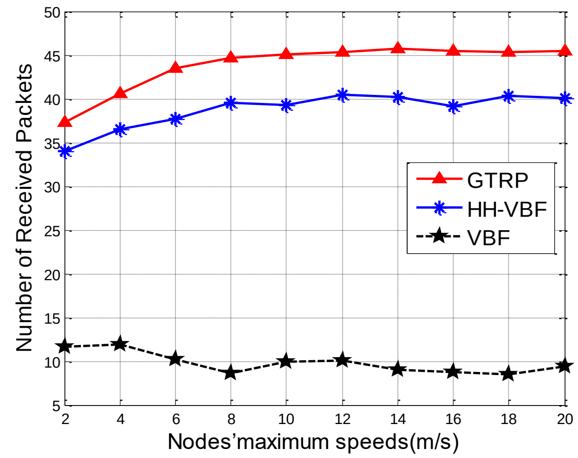

Fig. 15. Number of Received Packets

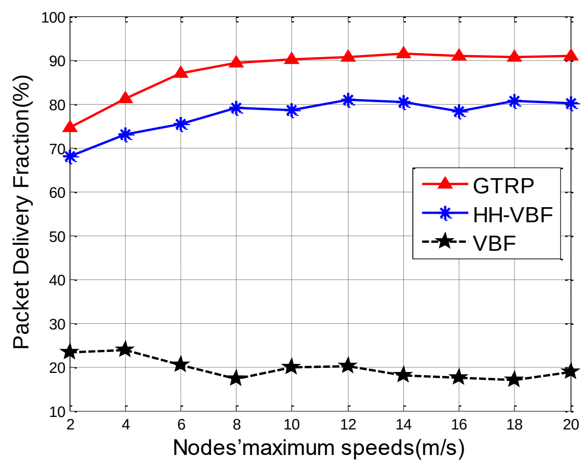

Fig. 16. Packet delivery Fraction

Fig. 17 shows the effects of the nodes' maximum speed on the average end-to-end. It is observed that GTRP performs better than HH-VBF and VBF. It is due to the fact that GTRP increases the number of packets received by destination nodes. Fig. 18 shows the results obtained for average energy consumption. It can be seen that the metric of GTRP is almost the same as that of HH-VBF, and better than that of VBF. GTRP adopts forwarding area and models the forwarding probability by game theoretic, and let the nodes closer to the destination forward, which consumes a lot of energy. Even though, GTRP increases the number of received packets. Fig. 19 demonstrates the results of the average collisions vs. the network density. As shown in the figure, VBF and HH-VBF perform better than GTRP. This is because VBF and HH-VBF adopt virtual pipeline, reducing the number of nodes participating in the forwarding process.

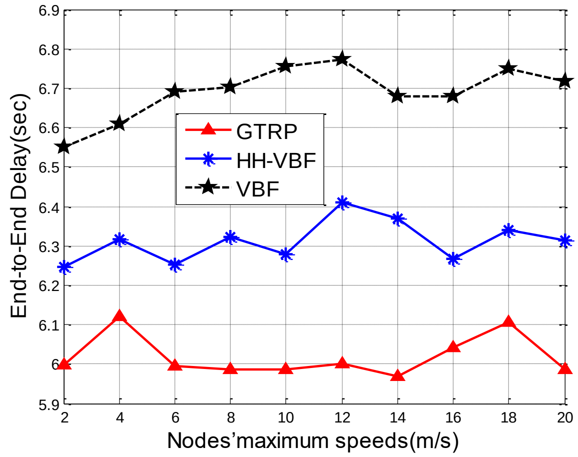

Fig. 17. End-to-End Delay

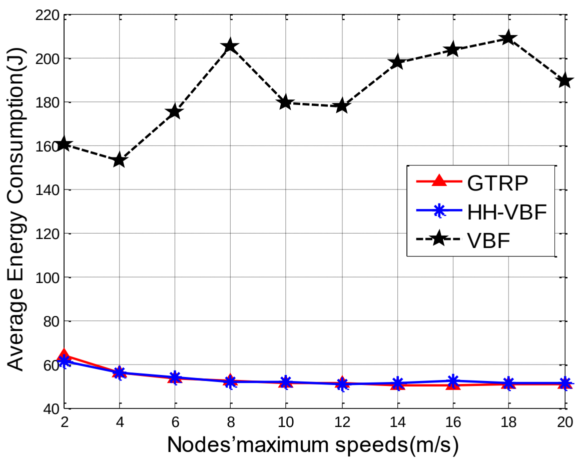

Fig. 18. Average Energy Consumption

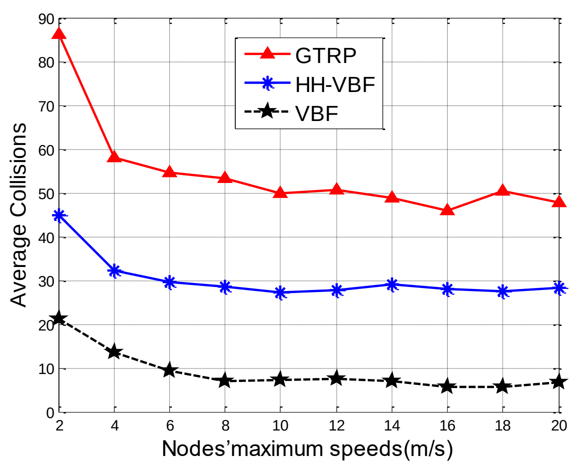

Fig. 19. Average Collisions

F. *Effects of the Interval of Sending Packet*

The purpose of the simulations presented in this subsection is to study the effects of the interval of sending packet on the performance of these protocols. The interval of sending packet changes between 10 s and 50 s. The value of the nodes' maximum speed is 3 m/s, and the number of nodes is 300.

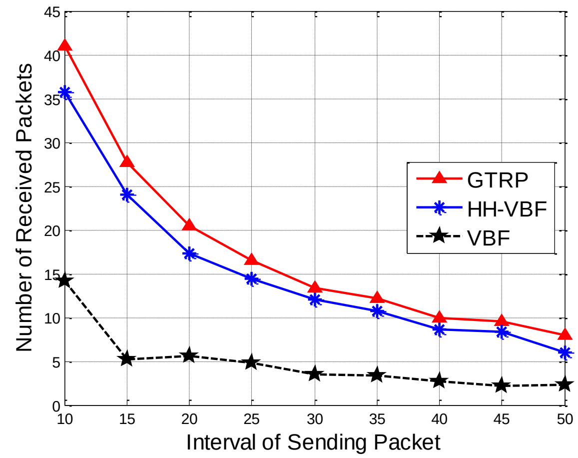

Fig. 20. Number of Received Packets

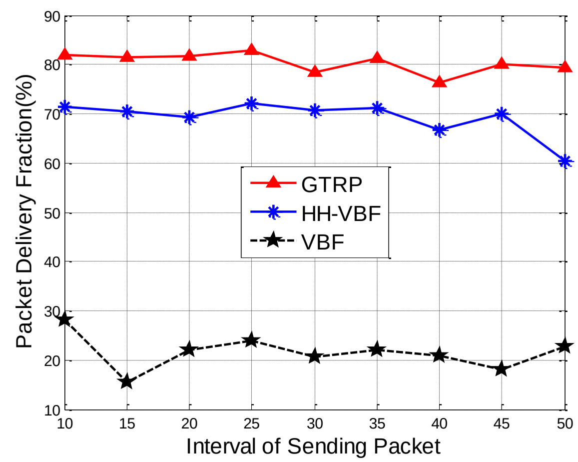

Fig. 21. Packet Delivery Fraction

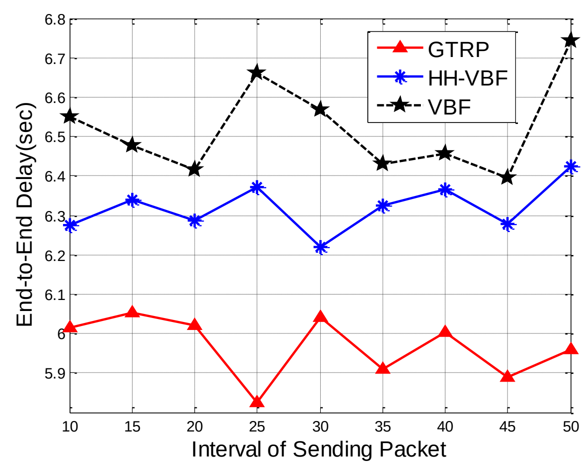

Fig. 22. End-to-End Delay

Fig. 20 presents the effects of the interval of sending packet on the number of received packets. It is obvious that the metric shows decrease tendency as the interval of sending packet increases. GTRP performs better than HH-VBF and VBF. As the interval of sending packet increasing, the number of packets sent by the source node decreases gradually, thus reduces the number of received packets. GTRP adopts forwarding area and the forwarding probability, and let the nodes closer to the destination forward, thus increases the number of the packets reaching the destination. Fig. 21 depicts the relationship between the interval of sending packet and packet delivery fraction. It is seen that the metric keeps stable as the interval of sending packet increases. GTRP protocol has the best performance. This is because GTRP increases the number of packets received by destination nodes by forwarding area and game forwarding strategy.

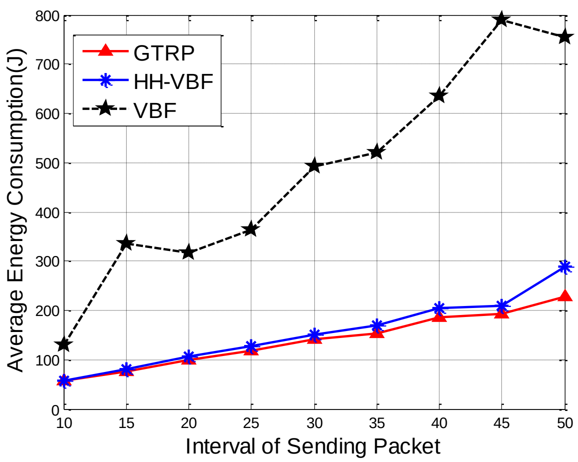

Fig. 23. Average Energy Consumption

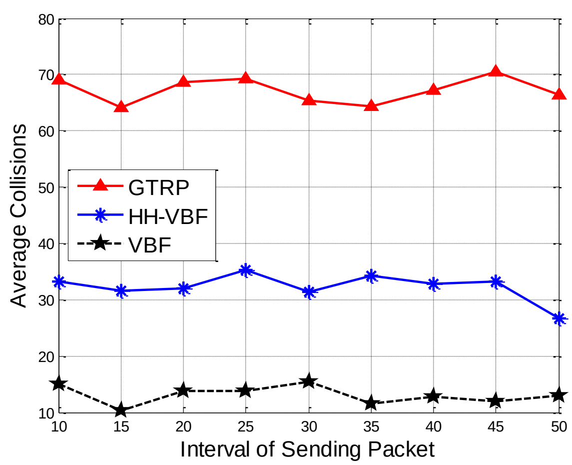

Fig. 24. Average Collisions

Fig. 22 shows the effects of the interval of sending packet on the average end-to-end. It is observed that the metric fluctuates with the interval of sending packet increasing. GTRP has better performance than HH-VBF and VBF. It is due to the fact that GTRP is not affected by network radius similar to HH-VBF and VBF, and let the nodes in the forwarding area participating in forwarding packets in a probabilistic manner, thus increases the number of packets received by the destination nodes. Fig. 23 illustrates the results of average energy consumption vs. the interval of sending packet. As shown in the figure, with the increase of interval of sending packet, the average energy consumption of the three protocols increases gradually. GTRP performs the best. This is because the GTRP protocol increases the number of packets received by the destination node, thus reduces the average energy consumption.

Fig. 24 demonstrates the results of the average collisions vs. the interval of sending packet. As shown in the figure, VBF and HH-VBF performs better than GTRP. This is because VBF and HH-VBF adopt virtual pipeline, reduce the number of nodes participating in forwarding process.

V. CONCLUSION

In this paper, we proposed a game theoretic routing protocol, named GTRP, for constructing 3D underwater acoustic sensor networks in the oceans. GTRP adopts forwarding area and game forwarding strategy, increases the forwarding efficiency. Simulation results show that GTRP performs better than HH-VBF and VBF in terms of the number of received packets, packet delivery fraction, end-to-end delay, average energy consumption. Collision avoidance mechanism and cross-lay design will be adopted in the novel version of our protocol in next phase of research work.

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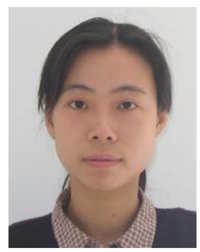

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