A Self-Adaptive Cooperative Routing Protocol for Underwater Acoustic Sensor Networks

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***Abstract*—Design an effective routing protocol in underwater acoustic sensor networks (UASNs) is an important issue. Long propagation time and low DATA rate which are two major concerns for routing protocol design in UASNs will lead to the long end-to-end transmission time. This paper proposes a Self-Adaptive Cooperative Routing Protocol (SACRP) to effectively route collecting DATA to the sink in UASNs. Cooperative transmission in SACRP not only can enhance the link quality (Signal-to-Noise Ratio (SNR)) to improve the network throughput but also can increase the transmission range of a node to reduce the end-to-end transmission time. Some mathematical analyses about cooperative transmission scheme are done to support SACRP protocol in the different DATA size and transmission range as well. Based on the network simulations, the proposed protocol, SACRP, has a significant performance against the related work in average end-to-end delay and packet delivery ratio.**

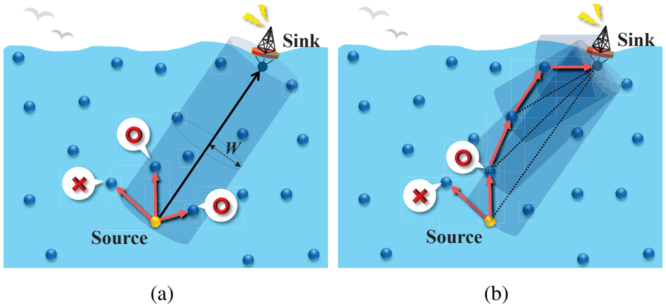
I. INTRODUCTION

Recently, underwater acoustic sensor networks (UASNs) has been widely applied to many fields, such as tactical surveillance and disaster prevention [1]. In these applications, underwater sensors are usually deployed within the areas of interest and are responsible for the detection and collection of sensing data. The collected data is usually time-critical and transmitted through acoustic signals in a single or multi-hop manner transmission to the sink.

However, due to the nature of the water, acoustic transmission in UASNs which is with low data rate and high propagation delay will lead to the long end-to-end transmission time than radio transmission in terrestrial wireless network. Moreover, sensor moves because of sea waves. As a result, how to reduce the end-to-end delay of a transmission has become the major concerned issue in designing a routing protocol for UASNs.

To support the time-critical applications, geographic routing [2] which is without routing table construction (DSDV [3]) or flooding for route discovery (AODV [4]) is one of the solution protocols. The main idea of geographic routing algorithm is that the neighboring sensor of the sender which is the geographically closest to the sink has the highest priority to forward DATA. To achieve this goal, two assumptions are needed in the geographic routing: (1) The sensor is aware of its location; (2) The location of sink is known by each sensor.

In [5]–[7], the sender exchanges the control message with the neighboring sensors to decide the forwarder and then directly transmits DATA to it. In addition, to reduce the control overhead, the neighbors of the sender are determined by themselves without control message exchanging when receiving DATA [8]–[10]. The qualified nodes will be the forwarder and keep forwarding DATA. However, the sound speed varies with the water depth, the ideal path which is with the minimum end-to end delay is not always the direct path from the source to the sink. In [8], sound speed in different water path is taken into consideration for routing. In addition, bit error rate also changes with the water depth. High bit error rate leads to a high probability of packet transmission failure. Therefore, the characteristics of sound speed and underwater noise are both considered in [10].



(a) (b)

Fig. 1. The concept of (a) VBF and (b) HH-VBF Routing Protocol. Multiple routing paths work inside the pipe to increase the robustness of DATA delivery.

When the UASNs are sparse, the routing hole may happen. To avoid the hole problem and further reduce control overhead, the routing pipe shown in Fig. 1 is created to increase the data delivery ratio in UASNs [11], [12]. Multiple routing paths are working in the pipe. However, the transmission from the redundant forwarders in the pipe will lead to the network congestion or collision when the UASNs are dense. Fortunately, the cooperative transmission scheme can make use of the advantage of the redundant transmission to enhance network performance.

Cooperative transmission which is a well-known scheme not only can enhance the link quality (Signal-to-Noise Ratio (SNR)) to improve the network throughput [13] but also can increase the transmission range of a node to reduce the end-to-end transmission time [14]. The main concept of cooperative transmission to achieve this goal is shown in Fig. 2. Suppose

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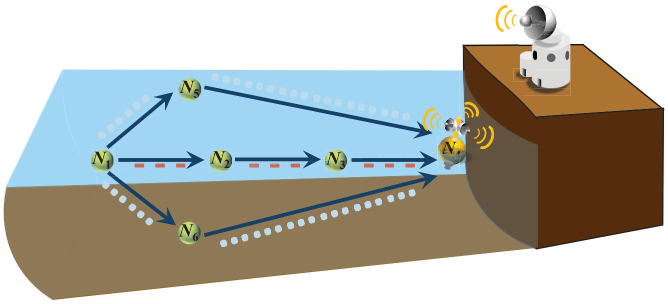

Fig. 2. The concept of cooperative transmission scheme in UASNs.

N_1 which is three hops away from N_4 has a packet to N_4. Instead of multi-hop forwarding by N_2 and N_3, N_5 and N_6 respectively investigate amplify-and-forward (AF) [14] or decode-and-forward (DF) [14] scheme to relay DATA after receiving from N_1. If the signals from N_5 and N_6 arrive to N_4 at the same time, the diversity combining techniques [13] can be used in N_4 to improve the packet quality.

As a result, a routing protocol, named a Self-Adaptive Cooperative Routing Protocol (SACRP), is proposed in this paper. SACRP takes the advantages of the cooperative transmission into consideration not only to enhance the probability of a successful transmission but also to reduce the end-to-end delay. The remainder of this paper is organized as follows: In Section II, the advantage of the cooperative transmission scheme is analyzed. The proposed routing protocol will be described in Section III. Section IV illustrates the performance evaluations and Section V concludes this paper.

II. PRELIMINARIES

To verify the effectiveness of the cooperative transmission scheme, some analyses are done in this section.

A. Estimation of Transmission Range with different number of cooperators

The impact of different number of cooperators to transmission range is discussed in this section. Based on [15], the relation between the transmitting power level (P_t) and the transmission range ($TR(f, P_t)$) is formulated as

$$TR(f, P_t) = \frac{W(\frac{P_t}{P_{th}} * \alpha(f))}{\ln \alpha(f)}, \tag{1}$$

where P_{th} is the signal strength threshold to receive the packet, $\alpha(f)$ is an absorption coefficient and is dependent on frequency f. W(z) is a Lambert W function. Suppose each cooperator transmits at the maximum transmission power (P_{max}). For simply, we also assume that each cooperator is at the same location. It implies that the receiving signal strength from each cooperator is identical in any location of UASNs. The receiving power level will be double if two cooperators are transmitting at the same time. Therefore, according to the previous assumption and Eq. (1), the analytical results are shown in Fig. 3.

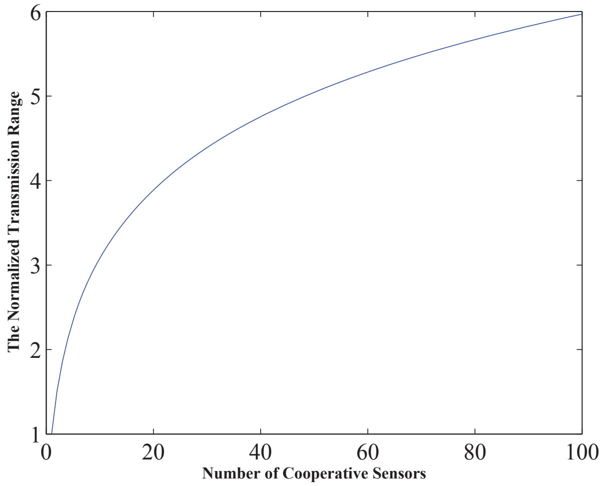

Fig. 3. The impact of different number of cooperators to transmission range.

We can observe that the transmission range will be approximately extended to 1.5 or 2.3 $TR(f, P_{max})$ when two or five sensors are cooperative transmitting, respectively. However, the improvement of transmission range is not significant, if 100 sensors are for cooperative transmission. The transmission range is just only extended to 6 $TR(f, P_{max})$. We can make a conclusion that two sensors for cooperation can get the best performance improvement.

B. Estimation of end-to-end transmission time improvement

Some symbols are defined before analyzing. The distance between N_1 and N_2 is denoted by d_{N_1,N_2}. T_{DATA} is the DATA transmission time. $T_{prop}^{N_1,N_2}$ is the propagation time from N_1 to N_2. To simply analyze the end-to-end transmission time in multi-hop forwarding and in cooperative transmission schemes, we assume that the network architecture is similar to Fig. 2. d_{N_1,N_2}= d_{N_1,N_5}=d_{N_1,N_6}=d_{N_2,N_3}=d_{N_3,N_4}. DATA rate is 10 Kbps and sound speed is 1500 m/s. The end-to-end transmission time in the multi-hop forwarding path ($N_1 \longrightarrow N_2 \longrightarrow N_3 \longrightarrow N_4$) can be evaluated as

$$3T_{prop}^{N_1,N_2} + 3T_{DATA}. \tag{2}$$

In addition, the end-to-end transmission time in the cooperative transmission path ($N_1 \longrightarrow (N_5, N_6) \longrightarrow N_4$) can be calculated as

$$3T_{prop}^{N_1,N_2} + 2T_{DATA}, \tag{3}$$

if d_{N_5,N_4}=d_{N_2,N_4}=$2d_{N_1,N_2}$.

Therefore, the analyzed results among different DATA sizes and transmission distances are shown in Fig. 4. We can observe that the larger the DATA size or the shorter the transmission distance is, the more transmission time enhancement gets. Note that the end-to-end transmission time has a significant improvement (20%) when the DATA size is 250 Bytes and the transmission distance is 200m. As a result, in this paper, we propose a Self-Adaptive Cooperative Routing Protocol for UWANs to reduce the end-to-end transmission time.

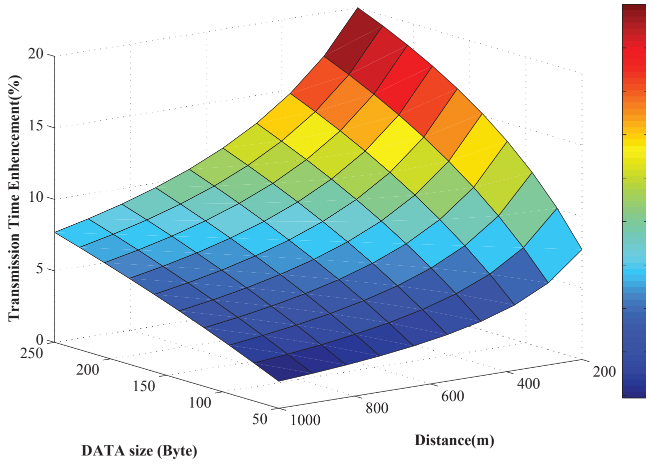

Fig. 4. The analyzed results among different DATA sizes and transmission ranges when d_{N_4,N_5}=d_{N_4,N_6}=2*$d_{N_i,N_{i+1}}$ (i=1 to 3).

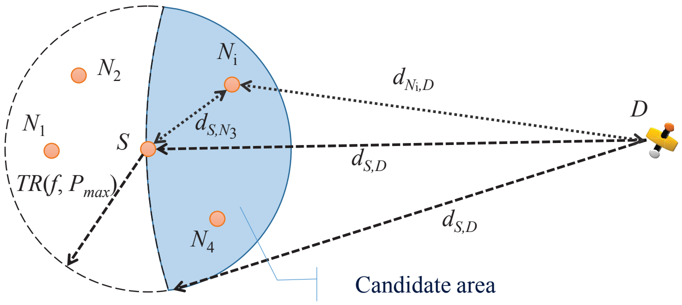

Fig. 5. The concept of candidate zone in SACRP.

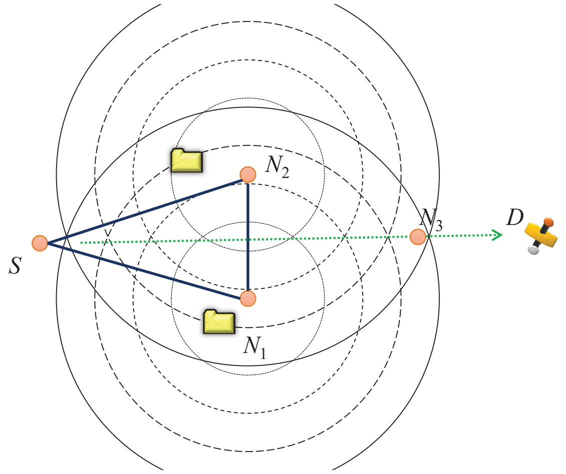

Fig. 6. The concept of cooperative line in SACRP.

III. THE PROPOSED SELF-ADAPTIVE COOPERATIVE ROUTING PROTOCOL (SACRP)

The two key issues, whom to cooperate and when to cooperate, should be addressed before designing the cooperative routing protocol.

A. Cooperator Selection

In fact, each neighboring node of the sender can be a candidate to cooperatively relay DATA for enhancing the quality of the receiving signal. However, not all of them are suitable for reducing the end-to-end transmission time. Taking Fig. 5 as an example to illustrate. Without loss of generality, S and D respectively indicate the sender and the destination. Due to the propagation time, if N_1 and N_2 are selected to relay DATA cooperatively, the length of the routing path is increasing, and the propagation time will significantly increase as well. As a result, in order to reduce the end-to-end transmission time, N_i which satisfies $d_{N_i,D} \leq d_{S,D}$ can be selected as candidate.

Take Fig. 6 as an example for further discussion. Suppose the cooperative node relays DATA immediately after receiving from the sender. If $d_{S,N_1} = d_{S,N_2}$, it implies that N_1 and N_2 are relaying DATA simultaneously. The signal will be enhanced along the perpendicular bisector of the line segment of N_1 and N_2 (green dot line). In SACRP, we call this green dot line as the cooperative line. If the node (N_3) which locates in the green dot line and $d_{N_1,N_3} \leq 2TR(f, P_{max})$, can successfully receive DATA from N_1 and N_2. Otherwise, the signal will be enhanced only at one location, the location of N_3, which should satisfy

$$d_{N_3,N_1} - d_{N_3,N_2} = d_{S,N_2} - d_{S,N_1}. \tag{4}$$

As a result, in order to increase the probability of finding the cooperative relays, we can conclude that two candidates, N_1 and N_2, have the highest priority to become the cooperative relay nodes if $d_{S,N_1} = d_{S,N_2}$, and $d_{N_1,D} = d_{N_2,D}$.

B. Cooperation Timing Decision

Because of the random deployment in UASNs, the direction of the cooperative line may not always toward the destination. In this case, the cooperative routing path will become longer than direct forwarding path if the cooperative transmission scheme is adopted. Therefore, in SACRP, we will adjust the transmission time of each cooperative relay node to reduce the end-to-end transmission time.

The concept of the adjusting transmission time scheme is shown in Fig. 7. Similar to Fig. 6, S and D are the sender and the destination in UASNs, respectively. Suppose N_1 and N_2 are selected as two relays, and $d_{S,N_1} < d_{S,N_2}$. A virtual sensor, N_1', is created which is located in the line from S to N_1, and $d_{S,N_1'}$ is equal to d_{S,N_2}. From the previous section, if N_1' and N_2 are selected as the relaying nodes and relay DATA at the same time, the signal will be enhanced along the perpendicular bisector of the line segment of N_1' and N_2. However, N_1' which is a virtual sensor can not transmit any DATA. In order to achieve this goal, we adjust the transmission time of N_1. If the time which the signal from N_1 crosses to N_1' is equal to the transmitting time of N_2, the signal will be enhanced along the perpendicular bisector of the line segment

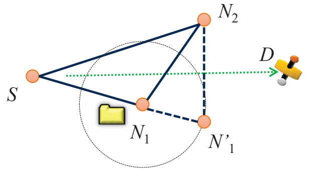

Fig. 7. The concept of cooperation timing decision in SACRP.

of N_1' and N_2 as well. The waiting time of N_1,$T_{waiting}^{N_1}$, after receiving from S can be calculated as

$$T_{waiting}^{N_1} = T_{prop}^{S,N_1} - T_{prop}^{S,N_2}. \tag{5}$$

For further extension to more relays for cooperative transmission, we choose a reference point S' which is located in the candidate zone and $d_{S,S'}$ as well as $d_{S',D}$ are the far distance.Therefore, we adjust the transmission time of each relay node N_i to relay DATA as

$$T_{waiting}^{N_i} = (T_{prop}^{MAX} - T_{prop}^{S,N_i}) + (T_{prop}^{S,D} - T_{prop}^{N_i,D}), \tag{6}$$

where, T_{prop}^{MAX} is the maximum propagation time.

C. Routing Protocol

The concept of SACRP is briefly shown in Algorithm 1. Make an example in Fig. 8 to illustrate. SACRP is composed of a directional transmission mode and a cooperative transmission mode. Suppose each node is aware of its location, and the location of sink is known by each sensor. When a node has DATA to transmit, it becomes the source node, S, and transmits DATA in the directional transmission mode. The information of transmission mode will be included in DATA packet. After receiving DATA, the sensors, N_1 to N_3, will distinguish the transmission mode. If the mode is directional transmission, N_1 to N_3 change the transmission mode in cooperative. Over a period of delaying time, $T_{waiting}^{N_i}$, they will cooperatively relay the receiving DATA. If a sensor, N_4, successfully receives the cooperative DATA from N_1 to N_3, it will work as the S in the directional transmission mode.

Algorithm 1 Self-Adaptive Cooperative Routing Protocol

```
/* When $N_i$ receives DATA */
switch DATA do
    case {DATA == Cooperative Transmission mode}
        Forward DATA;
    break
    case {$DATA$ == Directional Transmission mode}
        Relay DATA with $T_{waiting}^{N_i}$ delay;
    break
end switch
```

IV. PERFORMANCE EVALUATIONS

To verify the effectiveness of of SACRP, VBF [11] and HH-VBF [12] is simulated and compared. The simulation settings are shown in Table I.

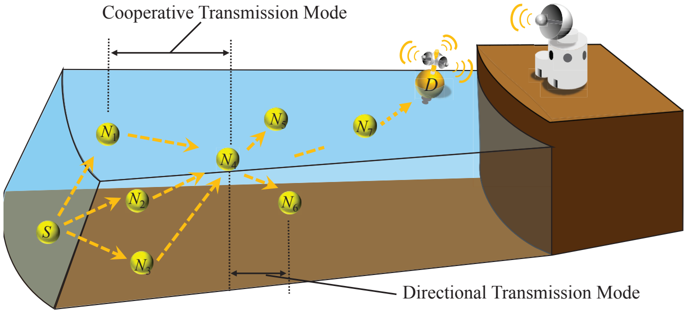

Fig. 8. The concept of SACRP.

TABLE I
SYSTEM PARAMETERS IN THE SIMULATIONS.

Parameter	**Value**
Simulation Area	30 Km X 30 Km
Sound Speed	1500 m/s
Data rate	10 kbps
Transmission range	3 km
Data packet size	1600 bits
Tx Power Consumption	2W
Rx Power Consumption	0.75W
Simulation Time	600s

Fig. 9 shows the comparison of VBF, HH-VBF and SACRP in terms of average end-to-end delay for different packet generation rate. Instead of the single routing vector in VBF, HH-VBF creates the hop-by-hop routing vector for each individual route in the network. The routing path of HH-VBF is shorter than that of VBF. Thus, HH-VBF can have the better performance than VBF. SACRP uses the cooperative transmission scheme to reduce hop counts in a route. As a result, SACRP has the best performance in end-to-end delay.

Fig. 10 shows the comparison of VBF, HH-VBF and SACRP in terms of packet delivery ratio for different packet generation rate. Because HH-VBF can find more paths for data delivery, we can see that the packet delivery ratio of HHVBF

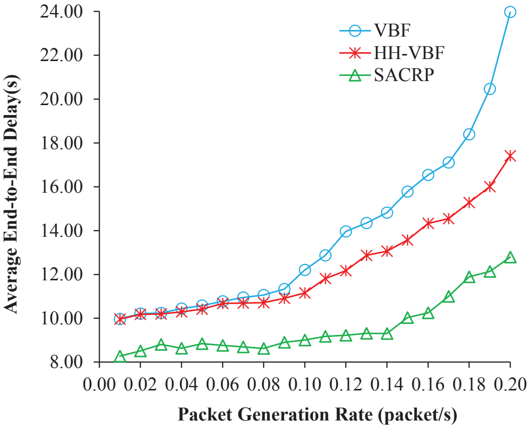

Fig. 9. The comparison of VBF, HH-VBF and SACRP in terms of average end-to-end delay for different packet generation rate.

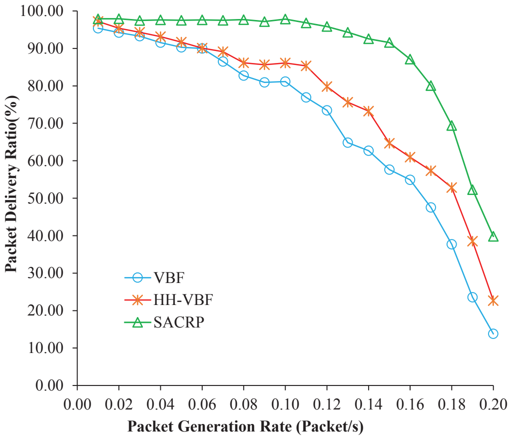

Fig. 10. The comparison of VBF, HH-VBF and SACRP in terms of packet delivery ratio for different packet generation rate.

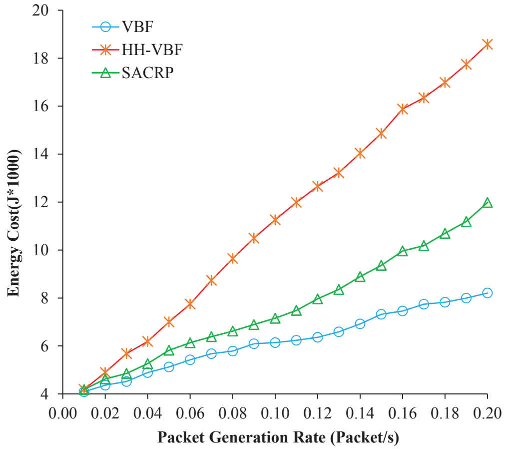

Fig. 11. The comparison of VBF, HH-VBF and SACRP in terms of energy cost for different packet generation rate.

is significantly improved upon VBF when the packet delivery ratio is high. SACRP can extend the transmission range to find the relay for routing. Therefore, SACRP also has the best performance in packet delivery ratio.

Fig. 11 shows the comparison of VBF, HH-VBF and SACRP in terms of energy cost for different packet generation rate. Due to more path for routing, we can observe that the energy cost of HH-VBF is significantly higher than that of VBF and SCARP, especially when the packet delivery ratio is high. However, in order to increase the packet delivery ratio and decrease the end-to-end delay, more relays simultaneous work for cooperation in SCARP. Thus, SACRP performs worse than VBF in energy cost.

V. CONCLUSIONS

Cooperative transmission is a novel technique for routing protocol design. Based on the mathematical analyses in this paper, when the number of cooperative relay is larger than 4, the transmission range will get a double extension, and the end-to-end transmission time will decrease 20 %. As a result, this paper proposes a Self-Adaptive Cooperative Routing Protocol (SACRP) to effectively route collecting DATA to the sink in UASNs. SACRP not only can enhance the link quality to improve the network throughput but also can increase the transmission range of a node to reduce the end-to-end transmission time. Cooperator Selection and Cooperation Timing Decision are also taken into consideration in SACRP. The simulation results show that SACRP has the best performance both in average end-to-end delay and packet delivery ratio.

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