Energy-Efficient Cooperative Routing in Underwater Acoustic Sensor Networks

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***Abstract*—This paper investigates performance of multi-hop underwater acoustic sensor networks when they deploy routing algorithms combining with cooperative communication. Taking into account energy efficiency, the routing schemes are discriminated by different policies of selecting next hop nodes as well as relay nodes of one-hop cooperative communications such that the transmission energy of routing paths is minimized. In order to take full advantage of broadcast nature in wireless communication, we propose to use a node exploited as a joint relay for two hop cooperative communication. Simulation results show that under specific conditions of acoustic channel, the network employing the proposed scheme achieves higher energy efficiency and balance of energy consumption among nodes while guaranteeing the desired data rate.**

***Index Terms*—Underwater Acoustic Sensor Network (UW-ASN), cooperative communication, energy efficiency, multi-hop network, power control, cooperative routing**

I. Introduction

Currently, Underwater Acoustic Sensor Networks (UW-ASNs) are deployed and used widely in significant oceanographic applications, such as military surveillance, marine resources and disaster preventions [1]. Besides limited available bandwidth, high bit error rates, one of the critical challenges faced by the UW-ASNs is limited energy resource since the sensors are usually powered by non-rechargeable battery [2]. In addition, for the acoustic sensors, the transmission energy is dominant in the total energy consumption (tens of Watts required for packet transmission, while only tens of mW or up to few Watts consumed by packet reception) [3]. Therefore, for saving energy of sensors, one solution is to reduce packet retransmissions.

In order to release the limitation, extensive researches have been conducted on both physical layer [4], [5], and network layer [6], [7]. The design of MAC protocols is another proposition. For example, deploying low duty cycle mechanisms allows the sensors to sleep for long periods [8] and [9]. Another studies as in [10] and [11] propose effective hand-shaking procedures to avoid packet collisions, thus prevent nodes from retransmit the packets.

Based on this analysis, the author proposes a new cooperative transmission scheme, namely wave cooperative transmission. The proposed protocol achieves a significant better performance than other protocols since the relay node amplifies received signal, and immediately forwards it to the destination without waiting the second time-slot. Meanwhile, M. Vajapeyam *et al*. [12] couple cooperative protocols and space-time block code strategies together. Their simulation results show that the proposed method achieves interesting performance in multi-path channels. Moreover, this approach can be easily implemented without the need of expensive equalization at the receiver. However, these works only focus on cooperative transmission in view of theoretical analysis, without addressing which communication links should be utilized.

On the physical layer perspective, limitation of size, cost and energy prevents underwater acoustic sensors from equipping multiple antennas. Thus, in order to enhance the acoustic link quality and reliability, cooperative communication taking advantage of broadcast nature of the wireless channel exploits relay nodes as virtual antennas [13]. Depending on the channel conditions and the expected communication quality, single relay or multiple relays can be selected properly to assist the communication between any source-destination pair. According to this communication technique, a receiver combines signals transmitted from a transmitter and relays overhearing the broadcasted signal of the transmitter to improve the reception quality, which in turn increases the probability of packet reception.

On the networking perspective, data transmitted in multi-hop manner is another way to achieve the energy efficiency of the UW-ASNs since the sensors benefit from lower transmission power in shorter distance of each hop. In addition, selection of next hop nodes in routing protocols can be optimized such that the total energy consumption of the routing paths is minimized [14]. Relying on the characteristics of the networks, these nodes are selected properly. For example, the sensor node that is closer to the sink and maximally away from the source is more likely to be selected as a next hop node in the routing protocol E-PULRP introduced in [15]. Meanwhile, according to the protocols proposed in [16], [17], the sensor nodes with the highest residual energy are assigned as relay nodes of routing paths.

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Unlike the previous works, this paper investigates the feasibility of combining routing and cooperative communication such that the network can obtain the energy efficiency as well as the desired data rate. Cooperation communication can be employed only for any one-hop communication since no direct link between the source and the destination in the network is available. Therefore, the data communication process involves both next hop node and cooperative relay node. Based on optimization problems formulated to minimize the total transmission energy of routing paths given the target data rate, the pairs of nodes are selected simultaneously.

The rest of this article is organized as follows. Section 2 describe the concerned network and its corresponding system model. The proposed scheme is described in Section 3. Section 4 presents the performance evaluation. Finally, a conclusion and future directions are drawn in Section 5.

II. System Model

A. Cooperative Communication with Single Relay

A single relay cooperative communication model in a wireless network consists of one transmitter (*Tx*), one relay (*R*) and one receiver (*Rx*), as depicted in Fig. 1.

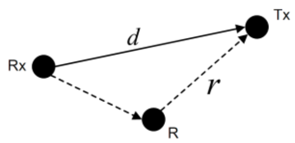

Figure 1. Cooperative communication scheme uses single relay node to forward data from a transmitter to a receiver

In this communication techniques, the overall process for data packet transmission consists of two phases. In the first phase, *Tx* transmits the data packet to the *Rx* by broadcast mode. In the second phase, the relay *R* uses cooperation protocols [13] to transmit the overheard packet to the *Rx*. The receiver *Rx* implements the maximal ratio combining (MRC) technique to combines the two signals (i.e., direct signal *d*, relay signal *r*) received from *Tx* as well as *R* to enhance the reception quality.

B. Multihop UW-ASN

This paper considers a simple two-hop UW-ASN as illustrated in Fig. 2, however it can be easily extended to a multi-hop scenario.

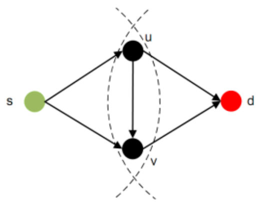

Figure 2. A simple two-hop network of underwater acoustic sensors

The data generated by the source (*s*) is routed to the destination (*d*) through their joint neighbor nodes *u; v* as next hop (*next_hop*) nodes since no direct communication channel between *s* and *d* is allowed. We denote *NB*(*i*), *NB*(*i;j*) as neighbor set of node *i* and joint neighbor set of two nodes *i*, *j*, respectively. Thus, the topology of network can be described by following neighbor sets: *NB*(*s*) = *{u, v}*, *NB*(*d*) = *{u, v}*, *NB*(*s; d*) = *NB*(*s*) ∩ *NB*(*d*) = *{u, v}*, *NB*(*u*)= *{s, d, v}*, *NB*(*v*) = *{s, d, u}*.

C. Cooperative Routing

This *section* describes different strategies to choose and combine *next_hop* nodes and *relay* nodes for joint routing and cooperation communication.

1) One relay for one-hop cooperative communication: In this sheme, one relay is used for each one-hop cooperative communication. Fig. 3 illustrates this scheme which chooses, for example, node *u* as *next_hop*, node *v* as *relay* for both the first hop and the second hop communication.

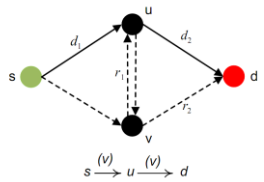

Figure 3. Cooperative Routing: single relay for one-hop cooperative communication

The overall communication process over routing path $s \xrightarrow{(v)} u \xrightarrow{(v)} d$ from *s* to *d* is as follow. In the first hop, *next_hop u* receives signals (d_1, r_1) transmitted by *s* and *v*. In the second hop, *d* combines signals (d_2, r_2) received from *u* and *v* respectively. In this network, although *v* plays a role in relaying for both two hop communication, the two relay signals may be different $(r_1 \neq r_2)$.

2) One joint relay for dual-hop cooperative communication: Instead of using two different relays for two-hop communication, we propose a scheme that exploits one joint relay for dual-hop communication as illustrated in Fig. 4.

The process of routing data from the source to the destination is as follows. In the first hop, u chosen to be next hop node receives signals (i.e.,d_1,r_1) from the source s and the relay v. In the second hop, u transmits the data to the destination in direct link (d_2). Meanwhile, the relay signal (r_1) from the joint *relay v* is exploited from the first hop.

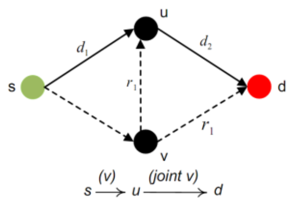

Figure 4. Cooperative Routing: joint relay for dual-hop cooperative communication

III. Transmission Energy Minimization of Routing Paths in Routing Algorithms

This section presents optimization formulations, which aim to minimize transmission energy of routing paths subject to the desired end-to-end data rate *R* (bits per second per Hertz).

Hereafter, p_{ij} and p_i^r are denoted as transmission power per packet from node *i* to node *j* and maximum allowed transmission power per packet of node *i* (p_i^r is constrained by the residual energy of the node *i*) respectively. G_{ij} and σ_{ij}^2 is defined as channel gain and noise power for the communication link between node *i* and node *j*; g_{ij} is the channel gain normalized by the noise power, g_{ij} = G_{ij} = σ_{ij}^2. Assuming that the source node s is aware of information (i.e., g_{ij}) of nodes in the network during the RTS/CTS packet exchange.

A. *Traditional Routing without Cooperative Communication*

In this scheme, no cooperative communication is employed, thus the data is routed from the source to the destination through the joint neighbor nodes *i* *(i ϵ NB(s, d))* as shown in Fig. 5.

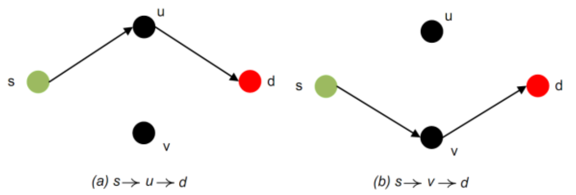

Figure 5. Two possible routing paths in the traditional routing scheme

The source node sends out the data to next hop node *i* with transmission power p_{si}, then the node *i* (*i ϵ NB*(*s*, *d*)) forwards this data with power p_{id} to the destination. Since the source is aware of its two-hop information, it can independently carry out a following optimization problem aiming to minimize the total transmission energy to transmit one data packet along the routing path $s \rightarrow i \rightarrow d$:

$$\textbf{Minimize} \quad f1i = \frac{L}{BR}(p_{si} + p_{id}) \quad (1)$$

$$p_{si}, p_{id} \quad log_2(1 + p_{si}\, g_{si}) \geq R \quad (2)$$

$$\textbf{subject to} \quad log_2(1 + p_{id} g_{id}) \geq R \quad (3)$$

$$0 \leq \{p_{si}, p_{id}\} \leq \{p_s^r, p_i^r\} \quad (4)$$

where *L* is the length of a data packets in bits, *b* is the bandwidth of acoustic channel, thus *L/BR* is the length of packet in seconds. The two conditions (2) and (3) ensure that the receivers should decode the received signals successfully. When the minimum transmission energy is found (i.e., $f1\min = \min_{i \in N\,B\,(s,d)}\{f1i\}$), the source node selects the efficient *next_hop* node as Algorithm 1.

Algorithm 1: Traditional Routing without Cooperative Communication

```
Input  : NB(s,d), p_i^r, g_ij, L, R, B
Output: next_ hop node of routing path
for i ∈ NB(s,d) do
    if f1_i = f1_min then
        next_hop ← i;
    end
end
```

B. *Cooperative Routing*

1) *Cooperative routing: One relay for one-hop communication*

In this routing scheme, supposing that node *i* is *next_hop* node and node *j* is joint *relay* node (if *i* is *u*, then *j* is *v* and vice versa). The total transmission energy of routing path (s $\xrightarrow{(j)}$ *i* $\xrightarrow{(j)}$ *d*) includes transmission energy from *s* to *i*, transmission energy from *j* to *i* for relaying, transmission energy from *i* to *d*, and transmission energy from *j* to *d* for relaying.

To obtain the target data rate (*R*) from *s* to *d* and energy efficiency of the network, the source allocates the transmission power of the nodes properly by minimizing the total transmission energy of routing path:

$$\textbf{Minimize} \quad f2i = \frac{L}{BR}(p_{si} + p_{ij} + p_{id} + p_{jd}) \quad (5)$$

$$p_{si}\, p_{ij}\, p_{id}, p_{jd} \quad 0 \leq \{p_{si}, p_{ji} + p_{jd}, p_{id}\} \leq \{p_s^r, p_j^r, p_i^r\} \quad (6)$$

$$\textit{subject to} \quad \frac{1}{2}(log_2(1 + p_{si}\, g_{si}) \geq R \quad (7)$$

$$\frac{1}{2}(log_2(1 + p_{si} g_{si} + p_{ij} g_{ij}) \geq R \quad (8)$$

$$\frac{1}{2}(log_2(1 + p_{id} g_{ij}) \geq R \quad (9)$$

$$\frac{1}{2}(log_2(1 + p_{id} g_{id} + p_{jd} g_{jd}) \geq R \quad (10)$$

The conditions (7) and (9) must be satisfied to ensure that the relay *j* can decode successfully the overheard signals broadcasted from *s* and *i*, respectively. When the optimization problem is solved, the *next_hop* and *relay* nodes can be selected by the source followed by Algorithm 2.

Algorithm 2: Cooperative Routing: single relay for one-hop communication

```
Input  : NB(s,d), p_i^r, g_ij, L, R, B
Output: next_ hop node and relay node
for i ∈ NB(s,d) do
    if f2_i = f2_min = min{f2_i} then
        next_hop ← i;
        relay ← NB(s,d) \ {i};
    end
end
```

2) *Cooperative routing: Joint relay for dual-hop cooperative communication*

In this scheme, the joint relay j provides the same relay signal to the both two hop (Fig. 4). Thus the total transmission energy of routing path (s $\xrightarrow{(j)}$ i $\xrightarrow{(joint\ j)}$ *d*) involves only p_{si}, p_{ji} and p_{id}. The optimization problem is formulated as following:

$$\textbf{Minimize} \quad f3_i = \frac{L}{BR}(p_{si} + p_{ji} + p_{id}) \quad (11)$$

$$p_{si}\, p_{ij}, p_{id} \quad 0 \leq \{p_{si}, p_{ji}, p_{id}\} \leq \{p_s^r, p_j^r, p_i^r\} \quad (12)$$

$$\textbf{subject to} \quad \frac{1}{2}log_2(1 + p_{si}\, g_{sj}) \geq R \quad (13)$$

$$\frac{1}{2}log_2(1 + p_{si}g_{si} + p_{ji}g_{ji}) \geq R \quad (14)$$

$$\frac{1}{2}log_2(1 + p_{id}g_{id} + p_{ji}g_{jd}) \geq R \quad (15)$$

Algorithm 3 allows the source node *s* to choose both *next_hop* node and joint *relay* node.

Algorithm 3: Cooperative Routing: joint relay for dual-hop communication

Input : $\mathcal{NB}(s,d)$, p_i^r, g_{ij}, L, R, B
Output: *next_hop* node of routing path and joint *relay*
for $i \in \mathcal{NB}(s,d)$ **do**
  if $f3_i = f3_{min} = min\{f3_i\}$ **then**
    $next\_hop \leftarrow i$;
    $relay \leftarrow \mathcal{NB}(s,d) \setminus \{i\}$;
  end
end

3) Condition for energy-efficient cooperative routing

Lemma 1. *The necessary condition for the network to obtain energy efficiency and desired data rate R by using single relay cooperation communication is that the channel gain of relay link (source →relay) is greater than that of direct link (source → destination).*

Proof. To prove it, we consider one-hop communication between *s* and *u* employing relay *v* for cooperation communication. The transmission energy of cooperation communication includes transmission energy of node *s* (p_{su}) and transmission energy of relay *v* (p_{vu}): $f_r = p_{su} + p_{vu}$. To achieve the desired data rate, the following conditions must satisfy:

$$\frac{1}{2}log_2(1 + g_{su}p_{su} + g_{vu}p_{vu}) \geq R \quad (16)$$

$$\frac{1}{2}log_2(1 + g_{sv}p_{su}) \geq R \quad (17)$$

$$0 \leq \{p_{su}, p_{vu}\} \leq \{p_s^r, p_v^r\} \quad (18)$$

Assuming that the conditions (18) are respected, the minimum transmission power of relay *v* satisfies:

$$g_{sv}p_{su}^{(min)} \leq 2^{2R} - 1 \quad (19)$$

If $g_{sv} \leq g_{su}$, then $g_{su}p_{su}^{(min)} \geq 22R$ - 1. That means that the condition (16) satisfies even p_{vu} = 0. In other word, there is no benefits of using the relay *v*. The lemma is proved.

IV. Simulation Results

This section presents numerical results showing the network performance in term of energy transmission in the routing algorithms. The underwater environment (i.e., shipping factor [0-1], wind speed [2-5(m/s)], etc.) [1] and the physical distance between nodes are varied to state the changeable channel gains g_{ij}). However, the network topology is kept unchanged. A set of g_{ij} is termed as a channel condition sample of network in this paper. The bandwidth *B* is 30 KHz and the target data rate *R* is 2 (bits/second/Hertz). The length (*L*) of data packet is 1000 bits.

A. Generic Channel Conditions of Network (Random Values of g_{ij})

Fig. 6 shows the minimum transmission energy for each routing path in the routing algorithm over 50 channel condition samples (i.e., 50 different sets of channel gains g_{ij}).

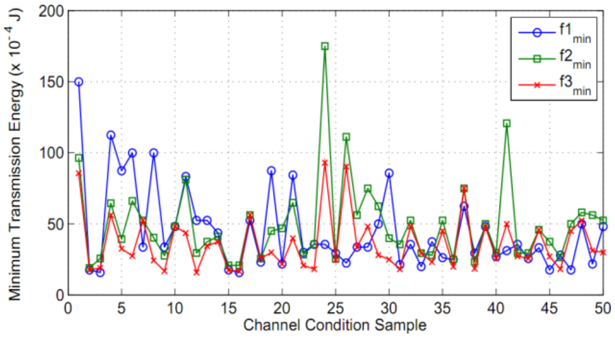

Figure 6. Minimum transmission energy of routing paths as a function of channel condition

Obviously, the minimum values is a function of channel condition reflecting the unreliable acoustic channel affected underwater environment (i.e., multi-path fading, movement of shallow water caused by shipping activities or wind, etc.).

B. Specific Channel Conditions of Network

Under the specific channel conditions of network characterized by conditions of Lemma 1, Fig.7 indicates the total transmission energy of routing paths for 29 samples extracted from the 50 samples of generic channel conditions.

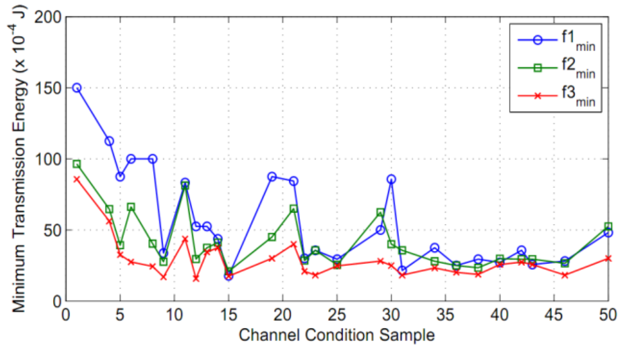

Figure 7. Minimum transmission energy of routing paths in samples of specific channel conditions ($g_{si} < g_{sj}$; $g_{id} < g_{jd}$, next_hop ← i, relay ← j, {i; j} ϵ NB(s, d))

Simulation result shows that Algorithm 3 (proposed scheme) outperforms both Algorithm 1 and Algorithm 2 in terms of energy efficiency since the relay signal for the second hop cooperation communication is exploited from the first hop transmission. In other word, in the second hop communication, the relay is in silent mode and saves its energy. Furthermore, in overall, deployment cooperative communication under the specific channel condition, routing data in the network benefits from lower transmission energy.

V. Conclusion

This paper investigates the UW-ASN performance in terms of energy efficiency under the impact of strategies of selecting both next hop nodes and relay nodes for one-hop cooperation communication. In order to save transmission energy of nodes, we propose to exploit a node used as joint relay for the dual hop cooperative communication. The simulation results show that our proposed scheme achieves higher energy efficiency given the desired data rate. As a future extension of this research, large scale multi-hop UW-ASNs are investigated when they deploy the proposed scheme to select the efficient pair (*next_hop* and *relay*) simultaneously.

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