Cooperative Transmission Scheme for Multi-hop Underwater Acoustic Sensor Networks

Do Duy Tan
Faculty of Electrical and Electronics Engineering
University of Technical Education Ho Chi Minh City,
Vietnam Email: tandd@hcmute.edu.vn

Dong-Seong Kim
School of Electronic Engineering
Kumoh National Institute of Technology, South Korea
Email: dskim@kumoh.ac.kr*
*Corresponding author

Abstract: In this paper, we propose a cooperative transmission scheme for multi-hop underwater (UW) acoustic sensor networks to enhance network performance. Relay nodes are employed as virtual antennas to achieve diversity gains. Based on the distinct characteristics of the UW channel, such as high transmission loss, propagation delay, and ambient noises, this paper presents a distributed cooperative scheme, including networking protocol and cooperative transmission at the physical layer, to enhance reliability by providing diversity gains through intermediate relay nodes. The destinations and potential relays are selected from a set of neighbor nodes that consider the distance cost and local measurement of the channel conditions into calculation. The simulation and numerical results show that the proposed scheme outperforms the traditional direct transmission schemes in terms of average energy consumption, packet delivery ratio, and end-to-end delay.

Keywords: Underwater acoustic sensor networks (UWASNs), cooperative networks, relay selection, signal-to-noise ratio (SNR).

Biographical notes:
Do Duy Tan received his M.S. degree at Networked Systems Laboratory, Kumoh National Institute of Technology, South Korea, in 2013. He received the Bachelor's degree from Ho Chi Minh City University of Technology, Vietnam, in 2010. He is currently a lecturer at Faculty of Electrical and Electronics Engineering, University of Technical Education Ho Chi Minh City, Vietnam. His main research interests are wireless communications and networking.

Dong-Seong Kim received his Ph.D. degree in Electrical and Computer Engineering from the Seoul National University, Seoul, Korea, in 2003. From 1994 to 2003, he worked as a full-time researcher in ERC-ACI at Seoul National University, Seoul, Korea. From March 2003 to February 2005, he worked as a postdoctoral researcher and visiting scholar at the Wireless Network Laboratory in the School of Electrical and Computer Engineering at Cornell University, NY. He was a visiting professor with department of computer science, University of California, Davis, U.S.A. Since 2004, he has been a professor in the School of Electronic Engineering and chair of mobile research center at Kumoh National Institute of Technology.
1 Introduction

Underwater (UW) acoustic communication has received increasing interest, which enables many oceanic investigations, commercial, and military applications (Akyildiz et al. (2005); Casari and Zorzi (2011); Misra et al. (2011)). However, the design of UW acoustic networks is considerably affected by the limited and distance-dependent bandwidth, poor quality of the links, and propagation delay (low speed of sound), which make UW communication different from that of the terrestrial wireless networks (Heidemann et al. (2008); Pompili and Akyildiz (2009); Dhurandher et al. (2009)). Many studies have developed networking solutions for UW acoustic networks, including acoustic channel modeling and physical layer transmission analysis (Zhang et al. (2008); Jamshidi (2011); Stefanov and Stojanovic (2011); Domingo and Vuran (2012)), as well as networking protocols (Pompili et al. (2006); Jornet et al. (2008); Pompili et al. (2009, 2010); Ayaz et al. (2012); Ojha et al. (2013)).

Cooperative diversity is a promising technique to improve the transmission diversity of wireless networks using low-complexity hardware (Xu et al. (2010)). The multiple-input multiple-output technique is an efficient approach that can increase the signal-to-noise ratio (SNR) by improving the spatial diversity gain. However, this approach requires hardware at each user (node) with higher cost and complexity. An alternative technique for spatial diversity is to exploit multiple nodes that cooperate to improve the quality of the communication channels (Laneman et al. (2004); Taghiyar et al. (2012)). In contrast to a single user with an array antenna, duplicated information is relayed by distributed antennas (called a virtual antenna array) via multiple nodes to reach the destination after some delay (Ahn and Lee (2011)).

Cooperative communication is a potential approach for distributed UW acoustic sensor networks (UWASNs) to enhance the link quality and reliability of both the point-to-point and networking communications, which contain two and multiple relay cooperation (Bletsas et al. (2006)). Our study considers the design aspect from the physical link to the network layer, leading to an efficient operation and reducing the transceiver's complexity in the cooperation diversity. Some previous studies applied the cooperative schemes for UWASNs (Han et al. (2008); Vajapeyam et al. (2008)). However, they only theoretically consider the cooperative transmissions of a point-to-point or a group of predefined source-destination connections and do not take into account the properties of the UW channel and the selection of a destination and appropriate relays among a large number of distributed nodes.

The most relevant research considered in our work is the relay selection scheme proposed in (Bletsas et al. (2006)). Bletsas et al. presented a single-relay selection model for a cooperative scheme, called opportunistic relaying, which combined the best relay selection with cooperative communication at the physical layer in wireless networks. Relay selection is involved in the discovery of appropriate relays that have the strongest paths for relaying information. To minimize the overall overhead of the relay nodes, the proposed scheme relies on the MAC-layer Request to Send (RTS)/Clear to Send (CTS) signals from the source and destination in the relay selection phase, whereas the relays overhear these messages.
to measure the instantaneous channel information and set up a timer that is inversely proportional to this channel quality. Once the timer at the relay acquires the best channel conditions, the timer measurement expires. It sends a flag packet to the source and to the other relays to inform them that is the best relay for cooperative communication. However, the relay selection phase based on the expired timers at the potential relays cannot be applied in a UW acoustic environment because of the large delay caused by the timer. Moreover, this model considers a group of nodes under the assumption that the destination node is decided and limited to a single transmission pair. Thus, it cannot be extended to multi-hop transmission scenarios.

To the best of our knowledge about cooperative transmission models and the characteristics of the UW communication, we take advantage of the cooperative transmission in UWASNs to overcome the channel limitations and to improve the network performance in terms of energy consumption, packet delivery ratio (PDR), and end-to-end delay under multi-hop transmission scenarios. The available relays and destination are discovered at the network layer based on the link state information at the link layer, which temporally depends on the wireless channel condition. The intermediate relays create additional diversity gains between the selected source and the destination from the neighbor nodes based on the distance cost to the sink and the local channel condition in the distributed topology. In general, our design aims to improve network performance in the following manner: (1) by applying cooperative transmissions to improve the reliability of the distributed UWASNs compared with those of the non-cooperative wireless communication; (2) by considering the specific characteristics of the UW and local channel conditions to design a simple destination-relay selection scheme at the network layer and the diversity-combining process with respect to the cooperative scheme; and (3) by using the simplicity of the technique that allows the applications of UWASNs without the need for additional hardware such as GPS systems or array antennas. This regular paper is an extension of conference version (Tan et al. (2013)) with more simulation results to specify the improvement of the proposed scheme in comparison with the compared algorithms.

The rest of this article is organized as follows. In Section 2, we introduce the network topology in connection with our scheme and the specific characteristics of the UW acoustic channels. Section 3 presents the destination and relay selection phase. The simulation settings and performance evaluation are presented in Section 4. In the final section, we conclude the paper.

2 Underwater Acoustic Channel

2.1 Attenuation and Propagation Delay

Sound propagates in the UW environment at an approximate speed of $c = 1500 \text{m/s}$. The UW communication channel is affected by the spreading and absorption losses, which cause considerable attenuation. For a distance $l$ (km) from the source to the destination at frequency $f$ (kHz) and spreading coefficient $k$, we calculate the attenuation $A(l, f)$ as described by Urick (Urick (1967)) following Eq. 1.

$$A(l, f) = l^k a(f)^L,$$  \hspace{1cm} (1)
where \( k \) is the spreading factor (\( k = 1 \) is cylindrical and \( k = 2 \) is spherical, and \( k = 1.5 \) in practical spreading). The absorption coefficient \( a(f) \) can be expressed by Thorp's formula (Berkhovskikh and Lysanov (1982))

\[
10 \log a(f) = \frac{0.11 f^2}{1 + f} + \frac{44 f^2}{4100 + f} + \frac{2.75 f^2}{4 - 0.003} \text{ [dB/km].}
\] (2)

2.2 Noise Model

UW communication is affected by many factors such as turbulence (\( N_T \)), shipping (\( N_S \)), waves (\( N_W \)), and thermal noise (\( N_{TH} \)), which can be modeled by the Gaussian statistics, and the power spectral density (PSD) of these ambient noises (in decibels re micropascal per hertz) as described in (Berkhovskikh and Lysanov (1982))

\[
10 \log N_T(f) = 17 - 30 \log f, \quad (3)
\]

\[
10 \log N_S(f) = 40 + 20(s - 0.5) + 26 \log f - 60 \log (f + 0.03), \quad (4)
\]

\[
10 \log N_W(f) = 50 + 7.5 \sqrt{w} + 20 \log f - 40 \log (f + 0.4), \quad (5)
\]

\[
10 \log N_{TH}(f) = -15 + 20 \log f, \quad (6)
\]

where the shipping activity factor \( s \) is in the range \([0 : 1]\), and \( w \) is the wind speed in m/s. Then, the overall ambient noise is

\[
N(f) = N_T(f) + N_S(f) + N_W(f) + N_{TH}(f). \quad (7)
\]

2.3 Capacity Limitation

From the definition of the total noise \( N(f) \) [W/Hz], we can evaluate the SNR at the receiver when the transmitted signal has a bandwidth \( B \) [Hz] and power \( P \) [W]. The bandwidth-limited SNR for link \( i - j \) is given by

\[
\text{SNR}(l, f) = \frac{P/A(l, f)}{N(f)B}. \quad (8)
\]

Assuming that the noise follows a Gaussian distribution and the channel is stable for some intervals of time (coherence time), the channel capacity of the Gaussian channel with infinite bandwidth represents the upper bound of the amount of information that can be transmitted successfully over a communication channel following the Shannon-Hartley theorem

\[
C(f, l) = B \log_2 \left( 1 + \frac{P/A(l, f)}{N(f)B} \right), \quad (9)
\]

where \( C(f, l) \) [bits/s] is the channel capacity, which depends on both frequency and distance. Assuming that the required transmission rate is \( R \) [bits/s], the signal is considered to be transmitted successfully over the fading channels when the channel capacity is greater than or equal to the transmission rate, given by

\[
C(f, l) \geq R. \quad (10)
\]

In this study, we adopt this concept as a condition in assessing the quality of the incoming signal at the receiver side. This method approximates the link efficiency of the wireless systems, without any need for complex coding, detecting, and decoding (Zhu and Zheng (2008)).
2.4 Network Topology

This paper considers a distributed UWASN in a shallow ocean, where the channel is heavily affected by multi-path fading. Data packets from the sensor nodes arrive at the surface gateway (sink), which communicates with the onshore center through long-range radio frequency (RF) or satellite communication. Each node can monitor and detect events from the local environment in many applications such as oceanographic data collection, pollution and environmental monitoring, and climate recording (Pompili and Akyildiz (2009)). We investigate its application in a water region of less than 100-m deep, where the signal can be modeled using a Rayleigh random variable (Pompili et al. (2010)). The presented scheme leads to a solution that enhances the reliability of the UW channel through the cooperative transmission scheme.

3 Underwater Acoustic Cooperative Transmission

3.1 Cooperative Transmission Model

The diversity system can be considered as a system that receives two or more similar copies of transmitted signals from a transmitter. In this study, we consider a cooperative scheme with two relays, as shown in Fig. 1, including one source, two relays, and one destination. Here, the relay method relies on regenerative cooperation where the relays attempt to detect and recover the original message from the source before forwarding the decoded bits to the destination (Ahn and Lee (2011)).

\[ H_{SR1}, H_{SD}, H_{R1D} (i = 1, 2), \]

**Figure 1** Two-relay cooperative transmission scheme with the channel responses from the source to the relays/destination and the relays to the destination are $H_{SR1}$, $H_{SD}$, $H_{R1D}$ ($i = 1, 2$), respectively.

In terrestrial wireless networks, the difference in propagation time is small and processed by the phase synchronization techniques. However, because of the high propagation delay in the UW acoustic, the addition scheme based on the analog domain fails because the three signals arrive at the destination at different times. The diversity-combining techniques are promising solutions to process the received signals at the destination for the UW acoustic communication, including selection diversity, maximal-ratio diversity, and equal-gain diversity systems (Brennan (2003)). The diversity techniques mitigate the effects of fading and improve the link quality of the wireless channel. These techniques are basically
designed for analog signals in radio communication where the propagation delay is much lesser than the processing delay at each node. However, signals in the UW environment move along multiple paths (relay and destination nodes) with different lengths and arrive at the destination at considerably different times. The addition model cannot be applied to the incoming signals at the destination in terms of the analog signals. Therefore, our scheme adapts the concept of diversity-combining techniques applied in the analog domain at the physical layer to the received signals at the packet level, which rely on the channel state information (CSI).

Several issues must be addressed in the cooperative scheme for the distributed UWASNs, including the following: (1) how to choose the destination and relays to efficiently forward the messages from the source to the final destination through cooperative connections, and (2) how to determine the required CSI to support the diversity combination at the destination. The following sections will describe the destination-relay selection process and the diversity-combining technique at the destination node.

### 3.2 Destination and Relay Selection

In previous studies (Bletsas et al. (2006); Zhou et al. (2008)), the source nodes try to find the best relay nodes to create cooperative transmissions for the terrestrial wireless networks, assuming that the destination is predefined. The approach based on the expired timers at the potential relays is not suitable for the UW acoustic channels because it remarkably increases the delay of the UW links. Furthermore, the channel conditions can be changed because of the long delay caused by the expired timers or the collision avoidance among the devices. This study investigates the cooperative transmissions in a distributed manner for the UWASNs. We assume that a source node, which must transfer its message toward the sink through a set of hops, has \( n \) surrounding nodes in its transmission range (neighbor nodes), as shown in Fig. 2. The source relies on the instantaneous channel conditions to determine which ones among the neighbors will be the most reliable paths to forward the information including both the destination and the relay nodes.

![Figure 2](image-url)  
*Figure 2* The network model with source and neighbors at each hop.
The selection process considers the channel properties, which include the SNR from each path to the source and the distance from each neighbor to the sink. We note that the GPS system, which is equipped for terrestrial wireless devices, cannot work well in the UW environment because of the limitations in the channel properties and frequency. The communication process consists of the following steps:

### 3.2.1 Building the List of Neighbors

Each node runs Algorithm 1 to build a list of neighbors with their respective hop count to the sink using advertising packets (ADV), which are periodically broadcast from the sink to all nodes after each predefined period. Based on the hop count to the sink, the source only forwards the packets to the sink through neighbors. The ADV packet plays a role in updating the connection status between the local and the surrounding nodes.

**Algorithm 1: Maintain the list of neighbors.**

```plaintext
1 Hop_count = \nabla^D_1(x);
2 Neighbor-table G;
3 if \(|G| = 0\) then
4     Add new neighbor as Parent to \(G\) including Hop_count;
5 else
6     if Hop_count < value on the table \(G\) then
7         Set Node Hop-count is Hop_count and the neighbor to be a Parent;
8     else if Hop_count = value on the table \(G\) then
9         Keep current Node Hop-count and the neighbor to be a Sibling;
10     else
11         Keep current Node Hop-count and the neighbor to be a Child;
12     Update new minimum Hop_count for sending ADV;
```

### 3.2.2 Gathering Channel Condition Information

Initially, when the source node contains data, it will broadcast an RTS packet to its neighbors (which are potential relays and destination) to relay the packet. The RTS/CTS length is small as compared with the length of the data packet to reduce the collision probability and energy consumption. The RTS contains the hop count of the source node to the sink. When a neighbor node receives the RTS, it compares its local hop count of the sink with that of the source. Only neighbors that have a smaller hop count than the source node can become the next relays, limiting the number of nodes joining in the competition to become relays/destination to reduce the energy consumption and packet loops. After checking the hop count field, potential relays reply with a CTS packet to the source. In this scheme, a node cannot measure the CSI between the destination and itself, as presented in (Bletsas et al. (2006); Zhou et al. (2008)) because of the undetermined destination. However, the channel condition from the relay to the destination is an important parameter that affects the relay selection. Thus, each node senses the surrounding channel conditions in terms of the SNR by overhearing the packets from its neighbors and inserts the average value into the CTS.
On the other hand, in the distributed scenarios, multiple sources can be required to send packets. The CTS from each neighbor suffers collision on the channels. Nevertheless, the sensing rate from the environmental events of each node is assumed to be small to reduce the packet collision. The source node estimates the SNR, and the time of arrival (ToA) in receiving the CTS packets corresponding to the respective neighbors. ToA is defined as the time that a packet moves from one node to another. This parameter is used to assess the physical distance from the source to the potential relays and the destination. In addition, the stored SNR value corresponding to a neighbor is the average between the SNR sensed from the CTS packet at the source and the averaged SNR estimated through overhearing packets of surrounding neighbors.

3.2.3 Destination-relay Selection

After the RTS/CTS exchange process, the source node obtains a list of candidates with ToA, and channel conditions. The source runs Algorithm 2 to select the appropriate relay nodes to forward the data message.

**Algorithm 2: Destination/Relays Selection.**

```plaintext
input : Hop_count, SNR, and ToA with respect to parents and siblings
output: The destination and two relays

1. max = total neighbors (n) with d(n) ≤ d(x);
2. for j = 1 to max do
3.   if C(f, l) ≥ R then // Satisfy requirement in Eq. 10
4.     if d(n) < d(x) then
5.       Add and sort by ToA in the list of parents;
6.     else
7.       Add and sort by ToA in the list of siblings; // d(n) = d(x)
8. Choose (top-down) 3 members from the list of parents and siblings for destination and two relays;
```

The parents and siblings are neighbors (n) whose hop_count is lower than and equal to the source node (x) on the path toward the sink, respectively. Only neighbors with a hop_count of less than or equal to the source are included into the relay calculation. Three parameters are used to evaluate a candidate, including hop_count, SNR, and ToA. First, the source checks the calculated channel capacity based on SNR corresponding to the neighbor to be added into the candidate list. In the next step, the algorithm checks whether the node is a parent or a sibling. Then, it is added to the respective lists and sorted by ToA. In addition, a timer is set up to receive CTS; the updating of the neighbor information will stop if a timeout occurs. When all candidates are checked or timed out, the source chooses three members to be the destination and the two relays. For a flexible method, the source can choose the destination/relays immediately after completing each list.

3.3 Diversity Combining Technique

The destination receives multiple replicas from the source transmission and relays. It can change between combining or non-combining model dynamically. It means that if the
original packet from the source is received successfully, the destination will directly forward the packet without combining process. Otherwise, a combining technique at the destination is needed to recover the original packet. The UW acoustic channel suffers from high propagation delay, which causes a large difference in the incoming signals. The paths of the source-relay-destination are considerably much longer than the direct source-destination path. Thus, the diversity-combing techniques are suitable approaches to process the signals at the destination, where the received signals from the source and relays are processed at the packet level, instead of the analog signals at the physical layer. The maximal ratio-combining (MRC) technique with BER estimation (Ilyas and Radha (2008); Ilyas et al. (2011)) is adopted to recover the messages from the source and intermediate relays.

![Diagram](image)

**Figure 3** Maximal Ratio Combining Diagram.

The MRC model is shown in Fig. 3, together with the diagram of the multiple-input-single-output system with three inputs at the receiver. We assume that the three arriving paths at times $t_1$, $t_2$, and $t_3$ are from the source, relay 1, and relay 2, respectively. At the destination, the received signals from the channel are demodulated and decoded to obtain the binary value $-b_i$ ($i = 1, 2, 3$). The detected binary sequences are then stored and multiplied by the respective weighted factors $(1 - P_i)$ to recover the original message from multiple replicas. In addition, bits are converted to a biased value $a_i$ before multiplying, where

$$a_i = \begin{cases} 1, & \text{for binary } 1, \\ 1, & \text{for binary } 0. \end{cases}$$  \hspace{1cm} (11)$$

The output binary value $b$ is determined by the sum $D_0$ based on the threshold, which is set to zero.

$$D_0 = \begin{cases} 3, & (1 - P_i) a_i. \\ 0, & D_0 < 0. \end{cases}$$  \hspace{1cm} (12)$$

$$X \begin{cases} b = 1, & D_0 \geq 0, \\ 0, & D_0 < 0. \end{cases}$$  \hspace{1cm} (13)$$

## 4 SIMULATION RESULTS AND PERFORMANCE EVALUATION

### 4.1 Simulation Settings

We evaluate the performance of the proposed scheme using OPNET Modeler 16.0 originally designed for terrestrial wireless communications. We modify the OPNET modeler to model
the physical properties of the UW acoustic channel, as discussed in Section 2.1, such as transmission loss, propagation delay, and noise model. The simulation parameters are listed in Table 1, following the related papers (Pompili et al. (2010); Xu et al. (2012)). A total of 100 UW sensor nodes were deployed in a three-dimensional area $300 \times 300 \times 100$ m$^3$ to detect and report events from the environment to the surface gateway equipped with both acoustic and RF modules to communicate with onshore stations. The sensor nodes operate at 30 KHz and a data rate of 10 Kbps, with a maximum transmission range of up to 100 m.

Table 1 Simulation Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment Type</td>
<td>Random Topology</td>
</tr>
<tr>
<td>Deployment Area</td>
<td>3-dimensional $300 \times 300 \times 100$ m$^3$</td>
</tr>
<tr>
<td>Number of Nodes</td>
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</tr>
<tr>
<td>MAC Protocol</td>
<td>802.11-based</td>
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<tr>
<td>Radio Power</td>
<td>0.5 W</td>
</tr>
<tr>
<td>Acoustic Range</td>
<td>100 m</td>
</tr>
<tr>
<td>Packet Size</td>
<td>200 B</td>
</tr>
<tr>
<td>Data Rate</td>
<td>10 Kbps</td>
</tr>
<tr>
<td>Frequency</td>
<td>30 KHz</td>
</tr>
<tr>
<td>Initial Energy</td>
<td>1000 J</td>
</tr>
<tr>
<td>Shipping Factor (s)</td>
<td>0.2</td>
</tr>
<tr>
<td>Wind Speed (w)</td>
<td>5 m/s</td>
</tr>
<tr>
<td>Number of Simulation</td>
<td>5</td>
</tr>
</tbody>
</table>

We adjust three pipeline stages in OPNET, including the propagation delay model, power model, and background noise model, related to the characteristics of the UW acoustic communication, as discussed in Section 2.1. Theoretically, the speed of sound in the UW environment depends on the temperature, salinity, and depth. However, for simplicity, we set it to the normal value of 1500 m/s. On the other hand, the power model takes into account the initial transmitted power, path loss, and antenna gains of the transmitter and receiver following Eqs. 1 and 2. The noise model of the UW channel $N(f)$, including turbulence, shipping, waves, and thermal noise, follow the overall PSD as shown in Eq. 7. The shipping factor and wind speed that cause noise are $s = 0.2$ and $w = 5$ m/s, respectively (Xu et al. (2012)).

At the MAC layer, we adapt the standard IEEE 802.11 ad hoc mode for medium access control in the UW environment, as presented in (Pompili et al. (2010, 2006)). However, all parameters of IEEE 802.11 are tuned to satisfy the characteristics of the physical UW acoustic channel. In addition, the exponential backoff algorithm is utilized in the IEEE 802.11 MAC to resolve the contention among different nodes that must access the channel. Each node can transmit its data when the backoff timer is exceeded, which is a random number of slots uniformly chosen in the interval $(0, CW - 1)$ (referred to as the contention window) before accessing the medium. The slot time is set to 20 $\mu$s for the IEEE 802.11 DSSS PHY. However, taking into consideration the distance between nodes and the high propagation delay in this model, we choose the slot time to be 0.18s. Furthermore, the contention windows $CW_{\text{MIN}}$ assigned at the first transmission and doubled at each retransmission up to $CW_{\text{MAX}}$ need to be changed to improve the low channel utilization due to the backoff contention mechanism. $CW_{\text{MIN}}$ and $CW_{\text{MAX}}$ are set to 4 and 32, respectively,
instead of 32 and 1024 similar to the terrestrial IEEE 802.11 DSSS (Pompili et al. (2006)). The source nodes generate messages with a packet length of 200 bytes according to a constant bit rate with different values of packet inter-arrival time (packets per second). The maximum transmit power is 0.5 W with an initial energy level of 1 kJ.

4.2 Numerical Results and Analysis

The proposed scheme (cooperative scheme) is compared with the minimum hop or the shortest path first (SPF) routing scheme (Dijkstra (1959)), based on the minimum number of hops required to reach the sink, and the proposed scheme without cooperative diversity (non-cooperative scheme) under three metrics: average energy consumption, PDR, and end-to-end delay.

4.2.1 Average energy consumption

The average energy consumption per bit for each received packet at the sink is computed as the ratio of the total amount of energy consumed by all nodes to generate/relay packets to the total number of packets that reaches the final destination (the sink) with different packet inter-arrival values. Figs. 4 and 5 show the average energy consumption per bit versus the packet inter-arrival time and the average residual energy per node versus time, respectively. The average energy consumption per bit in the proposed scheme (cooperative) is considerably smaller than those of the non-cooperative and SPF schemes. SPF relies on the shortest path to the sink; however, the packet is forwarded without considering the channel quality, which is affected by various types of noise in the UW channel. Thus, more retransmissions and energy consumption are required to reach the sink in sending a packet. On the other hand, the transmission scheme without cooperation between the relay nodes is based on the channel estimation that improves the received packet quality at the receiver node. However, transmission with one-path can be affected when the channel quality changes.

4.2.2 Packet delivery ratio

We evaluate the effects of the cooperative transmission model on the UW link in order to reduce the packet loss caused by the signal degradation over the medium channel. When the packet inter-arrival time is small, higher traffic is sent from the source nodes. This increases the packet collision, leading to a lower PDR. Fig. 6 indicates that the cooperative scheme achieves a higher PDR than the other schemes. The transmission without channel estimation in SPF causes higher packet loss. Moreover, the traffic that is focused on the paths with the minimum number of hops can cause more collisions and packet delay. The cooperative scheme improves the possibility of receiving packets successfully by forwarding the packets via multiple paths and combining them at the receiver node. The effect of the increase in the number of network nodes on the PDR is shown in Fig. 7. The higher the node density opens more opportunity to choose the best cooperative neighbors. The distance dramatically affects the attenuation in the UW channel. The higher node density indicates a shorter distance between nodes, which increases the signal strength at each receiver side. Nevertheless, when the node density becomes too high, it may cause more collision in the medium access control and interference among the nodes. Fig. 7 shows the effect of node density on the network performance. With a very low number of nodes, the PDR is reduced significantly because of the long distance among the nodes. Conversely, the PDR has the
highest value at around 140 nodes. A further increase in the node density may cause negative effects on the performance because of the packet collision and interference.

4.2.3 The Effect of end-to-end delay on the UW channel

The propagation delay in the UW channel causes high latency in the packets. The average end-to-end delay relative to the three schemes is shown in Fig. 8 when the packet inter-arrival time is set to 150 s. SPF forwards the packets with minimum hops, but the low-quality channel can increase the packet loss at the destination. Therefore, the packets have to be retransmitted, which increases the end-to-end packet delay. On the other hand, in the two schemes based on channel estimation, the packets are forwarded with higher reliability, which results in lower retransmissions, especially in the cooperative scheme. Thus, the
packet reaches the sink with shorter delay. Fig. 9 denotes the end-to-end delay versus various packet inter-arrival times, which indicates that the proposed cooperative scheme outperforms the other schemes in term of the increase in packet inter-arrival time. In particular, in high-traffic cases, the cooperative scheme considerably reduces the overall packet delay by 16% at inter-arrival time of 50 seconds.

5 CONCLUSIONS

UW acoustic networks are a potential area of networking in which the reliability and energy consumption are the most important issues. This paper has presented an adaptive scheme
of cooperative communication originally developed for terrestrial wireless networks to enhance the reliability of the communication link in the UW acoustic channel where the propagation delay strictly affects the diversity combination at the destination. The relay selection process considers link conditions and distance cost among the surrounding nodes to successfully relay the packets to the destination in a constrained environment such as that in UWASNs. This paper has presented the combination of multiple issues in the design from the physical to the network layer. It showed that the distributed cooperative scheme with a specific relay selection technique outperforms the traditional one-path communication in the resource-constrained wireless networks without additional hardware requirements, such as the GPS system or multiple antenna arrays. Hence, the cooperative diversity scheme reduces the complexity at the physical layer and enhances flexibility in implementation.
Further optimization is needed for future research on UWASNs, including the following: (1) integrating the cooperative communications with channel coding techniques to improve network performance; (2) considering other MAC layer protocols and efficient power allocation; and (3) analyzing further the network capacity under interference and collision among the devices.

Acknowledgments

This research was financially supported by National Research Foundation of Korea (NRF) through the Human Resource Training Project for Regional Innovation 2013 and Basic Science Research Program (NO. 2011-0025409).

References


Jamshidi, A. (2011) 'Direct sequence spread spectrum point-to-point communication scheme in underwater acoustic sparse channels', *IET Communications*, Vol. 5, pp.456-466


Uruck, R. J. (1967) 'Principles of underwater sound for engineers', *McGraw-Hill*


