Distributed Cooperative Transmission for Underwater Acoustic Sensor Networks

Do Duy Tan, Tung Thanh Le, and Dong-Seong Kim
Department of IT Convergence, School of Electronic Engineering
Kumoh National Institute of Technology, South Korea
Email: {tandd, ttungl, dskim}@kumoh.ac.kr

***Abstract*—In this paper, we propose a cooperative transmission scheme for underwater acoustic sensor networks to enhance the network performance. Relay nodes are exploited as virtual antennas to achieve diversity gains. Based on the distinct characteristics of the underwater channel such as high transmission loss, propagation delay, and ambient noises, the paper presents a distributed cooperative scheme including networking protocols and cooperative transmissions at the physical layer in order to enhance the reliability by providing diversity gains through intermediate relay nodes. Destinations and potential relays are selected from a set of neighbor nodes that utilize 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.**

***Index Terms*—Underwater acoustic sensor networks (UW-ASN), cooperative networks, diversity, signal-to-noise ratio (SNR), energy consumption, packet delivery ratio.**

I. Introduction

Underwater acoustic communication has been received an emerging interest to enable many oceanic researches, commercial and military applications. However, the design of underwater acoustic networks is significantly affected by the limited and distance-dependent bandwidth, the poor quality of the links, and propagation delay (low speed of sound) which make underwater communication different from terrestrial wireless networks [1]. Many studies have been investigated on developing networking solutions for underwater acoustic networks, including acoustic channel modeling and physical layer transmission analysis [2], [3] as well as networking protocols [4], [5].

Wireless system designs consider the degree of diversity to enhance the successful transmissions by providing more duplicated signals at the receiver. Multiple-Input Multiple-Output (MIMO) technique is an efficient approach to increase the signal to noise ratio (SNR) by improving 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 cooperating to improve the quality of communication channel [6]. In contrast to a single user with an array antenna, duplicated information is relayed by distributed antennas (called a virtual antenna array) by multiple nodes to reach the destination after some delay [7].

Cooperative communication is a potential approach for distributed UW-ASN to enhance the link quality and reliability in both point-to-point and networking communication, containing two and multiple relays cooperation [8]. Our study considers a design aspect from the physical link to the network layer, leading to the efficient operation and reducing transceiver's complexity in cooperation diversity. Some previous papers exploit cooperative schemes for UW-ASN [9], [10]. However, they only consider cooperative transmissions under the view of theoretical analysis for point-to-point or a group of predefined source-destination connections. Otherwise, these works do not clearly take into account the properties of the underwater channel and how to select a destination and appropriate relays among a great number of distributed nodes.

To the best of our knowledge about cooperative transmission models and the characteristics of the underwater communication, we take advantage of cooperative transmission into underwater acoustic sensor networks to overcome the channel limitations and to improve the network performance in terms of energy consumption, packet delivery ratio, 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 (LSI) at the link layer, which timely depends on the wireless channel condition. The intermediate relays create the additional diversity gains between the selected source and destination from neighbor nodes based on the distance cost to the sink and local channel condition in distributed topology. Generally, our design aims to improve the network performance by (1) applying cooperative transmissions to improve the reliability for distributed underwater sensor networks compared to non-cooperative wireless communication; (2) considering the specific characteristics of the underwater channel and local channel conditions to design a simple destination/relays selection scheme at the network layer and diversity combining process with respect to cooperative scheme; and (3) the simplicity of the technique allows the applications of underwater sensor networks that need no additional hardware requirements such as GPS systems or array antennas.

The rest of this article is organized as follows. In Section II, we introduce the network topology with consideration in our scheme and specific characteristics of the underwater acoustic channels. Section III presents the destination and relay selection phase. Simulation settings and performance

978-1-4799-0110-4/13/$31.00 ©2013 IEEE

evaluation are conducted in Section IV. In the final Section, we conclude the paper.

II. Underwater Acoustic Channel

A. Attenuation and Propagation Delay

Sound propagates in the underwater environment at approximate speed $c = 1500m/s$. Underwater communication channel is affected by spreading loss and absorption loss which cause significant attenuation. For a distance l (km) from a source to a destination at a frequency f (kHz) and spreading coefficient k, we calculate the attenuation $A(l, f)$ as described by Urick [11] following Eq. 1.

$$A(l,f) = l^k a(f)^l, \tag{1}$$

where k is the spreading factor ($k = 1$ is cylindrical, $k = 2$ is spherical, in practical spreading $k = 1.5$). The absorption coefficient $a(f)$ can be expressed by Thorp's formula [12],

$$10loga\left(f\right) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + \frac{2.75f^2}{10^4} + 0.003\left[dB/km\right]. \tag{2}$$

B. Noise Model

Underwater communication is affected by many sources such as turbulence (N_t), shipping (N_s), waves (N_w) and thermal noise (N_{th}) which can be modeled by Gaussian statistics and the power spectral density (PSD) of those ambient noises (in dB re μ Pa per Hz) as described in [12]:

$$10logN_t\left(f\right) = 17 - 30logf, \tag{3}$$

$$10logN_s\left(f\right) = 40 + 20(s - 0.5) + 26logf - 60log(f + 0.03), \tag{4}$$

$$10logN_w\left(f\right) = 50 + 7.5\sqrt{w} + 20logf - 40log(f + 0.4), \tag{5}$$

$$10logN_{th}\left(f\right) = -15 + 20logf, \tag{6}$$

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

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f). \tag{7}$$

C. Capacity Limitation

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

$$SNR\left(l,f\right) = \frac{P/A(l,f)}{N(f)B}. \tag{8}$$

Assuming that the noises follow Gaussian distribution and the channel is stable for some interval of time (coherence time). Then, the channel capacity of a Gaussian channel with infinite bandwidth represents the upper bound on the amount of information that can be transmitted successfully over a communication channel following Shannon-Hartley theorem:

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

where $C\left(f,l\right)$ $[bits/second]$ is the channel capacity which depends on both frequency and distance. With the assumption that the transmission rate at each node is R $[bits/second]$, the signal is considered to be transmitted successfully over fading channels if the channel capacity is greater than or equal to the transmission rate, given by:

$$C\left(f,l\right) \geq R. \tag{10}$$

In this study, we adopt this concept as a condition to assess the quality of incoming signal at the receiver side. This method approximates the link efficiency in wireless systems without any requirement in complex coding, detecting, and decoding procedures.

D. Network Topology

The paper considers a distributed underwater acoustic sensor network in the shallow ocean, where the channel is heavily affected by multi-path fading. Data packets from sensor nodes arrive at the surface gateway (sink) which can communicate with the onshore center through the long range radio frequency or satellite communications. Each node can monitor and detect events from local environment in many applications such as oceanographic data collection, pollution and environmental monitoring, climate recording, etc. [1]. We investigate on the applications in the water region less than 100m in depth where the signal can be modeled by a Rayleigh random variable. The presented scheme leads to a solution in order to enhance the reliability of the underwater channel through cooperative transmission scheme.

III. Underwater Acoustic Cooperative Transmission

A. Cooperative Transmission Model

Diversity system can be referred as a system that receives two or more similar copies of transmitted signals from a transmitter. In this paper, we consider a cooperative scheme with two relays as shown in Fig. 1, including one source, two relays, and one destination. Herein, the relay method relies on the regenerative cooperation where the relays attempt to

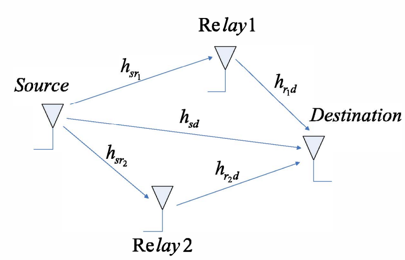

Fig. 1. Two-relay cooperative transmission scheme with the channel responses from the source to the relays/destination and the relays to the destination are h_{sr_i}, h_{sd}, h_{r_id} ($i = 1, 2$), respectively.

detect and recover the original message from the source before forwarding decoded bits toward the destination [7].

In terrestrial wireless networks, the difference in propagation time is small and processed by phase synchronization techniques. However, due to the high propagation delay in the underwater acoustic, the addition scheme based on analog domain fails because three signals arrive to the destination at the different times. Diversity combining techniques are promising solutions to process received signals at the destination for underwater acoustic communication including selection diversity, maximal-ratio diversity, and equal-gain diversity systems [13]. It is seen that diversity techniques mitigate the effects of fading and improve the link quality of wireless channel. These techniques are basically designed for analog signal in radio communication which the propagation delay is much less than the processing delay at each node. However, signals move along multiple paths (relay and destination nodes) with different length and arrive the destination at considerably different times in the underwater environment. It cannot be applied the addition model to the incoming signals at the destination in terms of analog signals. Therefore, our scheme adapts the concepts of diversity combining techniques that are applied for analog domain at the physical layer to the received signals at the packet level relying on the channel state information (CSI).

B. Destination and Relay Selection

In previous studies [8], [14], the source nodes try to find the best relay nodes in order to create cooperative transmissions for terrestrial wireless networks with the assumption that the destination is predefined. The approach based on the expired timers at potential relays, is not suitable for the underwater acoustic channels because it remarkably increases the delay for underwater links. Furthermore, the channel conditions can be changed due the long delay causing by expired timers or the collision avoidance among the devices. This paper investigates on cooperative transmissions in a distributed fashion for underwater acoustic sensor networks. We assume that a source node, which needs to transfer its message toward the sink through a set of hops, has n surrounding nodes in its transmission range (neighbor nodes) as illustrated in Fig. 2. The source relies on the instantaneous channel conditions to determine which ones among neighbors will be the most reliable paths to forward the information toward the sink including both destination and relay nodes.

The selection process takes into account the channel properties, which includes the SNR (signal-to-noise ratio) from each path to the source and the distance from each neighbor to the sink. It is noted that the GPS system, which is equipped for terrestrial wireless devices, cannot work well in the underwater environment due to the limitations of the channel properties and frequency. The communication process consists of six steps: RTS sending, CTS receiving, source-based calculations, source transmission, relay transmission, and acknowledgement.

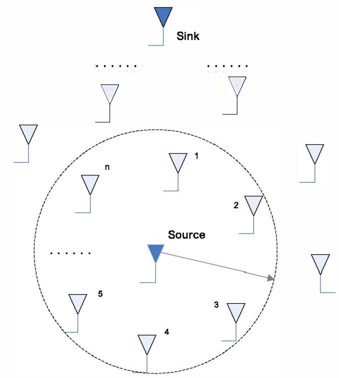

Fig. 2. The network model with source and neighbors at each hop.

1) Building the list of neighbors: Each node builds a list of neighbors with respective hop count, called distance interchangeably, to the sink by advertising packet (ADV) which is periodically broadcast from the sink to all sensor nodes after each predefined period of time. Based on the hop count to the sink, the source only forwards packets toward the sink through a group of relative neighbors. After the initial time, the network status is stable; the ADV packet plays a role of updating the connection status between local nodes and surrounding nodes.

2) Gathering Channel Conditions: At first, when the source node has data, it will broadcast a RTS (Request to Send) packet to its neighbors which are potential relays and destination to relay the packet. The length of RTS/CTS is small if compared to the data packet's length to reduce energy consumption for surrounding nodes. The RTS packet contains the hop count of the source node to the sink. Since a neighbor node receives a RTS packet, it compares its local hop count to the sink with the hop count of the source. Only neighbors that have smaller distance than the source node can become the next relays. This limits the number of nodes joining into the competition to become relays/destination in order to reduce energy consumption and packet loops. After checking the distance field, the potential relays reply a CTS (Clear to Send) packet toward the source. Noting that in this scheme, a node cannot measure the channel state information between itself and the destination as in [8], [14] due to the undecided destination. However, the channel condition from a relay to the destination is an important parameter which affects on the relay selection. Thus, each node senses surrounding channel conditions in terms of SNR by overhearing packets from its neighbors and inserts the average value into the CTS.

On the other hand, in distributed scenarios, multiple sources can be required to send packets, the CTS from each neighbor suffers to collide on channels. Nevertheless, the sensing rate from environment events of each node is assumed to be small in order to reduce the packet collision. The source node estimates the SNR ratio, time of arrival (ToA) when receiving these CTS packets corresponding to the respective neighbors. The ToA is defined as a packet moves from a node to another one. This parameter is used to assess the physical distance from a source to potential relays and the destination. In addition, the SNR value stored corresponding to a neighbor is averaged between SNR sensed from CTS packet at the source and the averaged SNR that estimated through overhearing at each neighbor.

3) Destination/Relays Selection: After the RTS/CTS exchange procedure, the source node achieves a list of candidates with the distance, ToA, and channel conditions, respectively. The source runs Algorithm 1 to select the appropriate and reliable relay nodes to forward the data message.

Algorithm 1: Destination/Relays Selection.

input : Hop_count, SNR, and ToA with respect to parents and siblings

output: The destination and two relays

```
max = total neighbors (n) with d(n) ≤ d(x);
for j = 1 to max do
    if C(f,l) ≥ R then            // Satisfy requirement in Eq. 10
        if d(n) < d(x) then
            Add and sort by ToA in the list of parents;
        else
            Add and sort by ToA in the list of siblings ; // d(n) = d(x)
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 hop_count less than or equal to the source are joined into the relay calculation. Three parameters are utilized to evaluate a candidate including hop_count, SNR, and ToA. First, the source checks the calculated channel capacity corresponding to the neighbor and the required data rate to be added into the candidate list. The next step, the algorithm checks if the node is a parent or sibling. Then, it is added to the respective lists and sorted by ToA. Besides, a timer is set up for receiving CTS, the neighbor information updating will stop if timeout occurs. Until all candidates are checked or timeout, the source chooses 3 members to be a destination and two relays from those two lists in turn. For a flexible method, the source can choose the destination/relays immediately after finishing each list.

C. Diversity Combining Technique

Underwater channel suffers the high propagation delay which causes the large difference for incoming signals. The paths with source-relay-destination are considerably much longer than the direct source-destination path. Thus, diversity combing techniques are suitable approaches to process signals at the destination, where received signals from source and relays are processed at the packet level, instead of analog signals at the physical layer. The intermediate relays decode the message from the source in the first phase and forward it in the next phase. The destination then receives multiple replicas from source transmission and relays. The maximal ratio combing technique is applied to recover messages from the source and intermediate relays. We adopt the BER estimation model in [15] to predict the BER of packets whose parameters are estimated by using the maximum likelihood estimation (MLE).

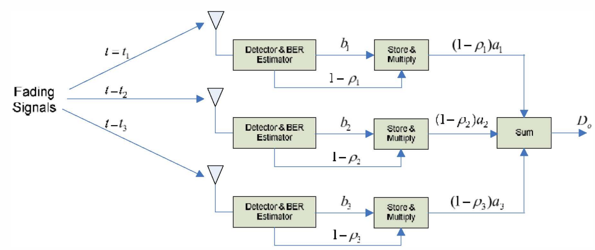

Fig. 3. Maximal Ratio Combining Diagram.

The maximal ratio combining can be similarly described in Fig. 3 to diagram for Multiple-Input Single-Output (MISO) system with three inputs at a receiver. We assume that three arriving paths at times t_1, t_2, t_3 are from the source, the relay 1, and the relay 2, respectively. At the destination, the received signals from channel are demodulated and decoded to obtain a binary value - b_i $(i = 1, 2, 3)$. The detected binary sequences are then stored and multiplied by respective weighted factors $(1-\rho_i)$ to recover the original message from multiple replicas. In addition, bits are also converted to a biased value a_i before multiplying, where

$$a_i = \begin{cases} 1, & \text{for binary } 1, \\ -1, & \text{for binary } 0. \end{cases} \tag{11}$$

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

$$D_o = \sum_{i=1}^{3} (1 - \rho_i)\,.a_i, \tag{12}$$

$$b = \begin{cases} 1, & D_o \geq 0, \\ 0, & D_o \text{ ¡ } 0. \end{cases} \tag{13}$$

IV. SIMULATION AND EVALUATION

A. Simulation Settings

We evaluate the performance of the proposed scheme by OPNET Modeler 16.0 originally designed for terrestrial wireless communications. The simulation parameters are referred to related papers [4], [16]. 100 underwater sensor nodes are implemented in a 3-dimensional 300×300×100 m^3 to detect and report events from the environment to the surface gateway equipped with both acoustic and RF modules in order to communicate with onshore stations. Sensor nodes operate at 30 KHz and data rate at 10 Kbps with the maximum transmission range up to 100 meters.

We adjust three stages, including propagation delay model, power model, and background noise model, that are related to the characteristics of the underwater communication in OPNET as regarded in Section II-A. Theoretically, the speed of sound in the underwater environment depends on temperature, salinity and depth. However, for simplicity, it is set to a normal value at 1500 m/s. On the other hand, the power model takes into account the initial transmitted power, path loss, and antenna gains at the transmitter and receiver following to Eqs. 1 and 2. The other one, the noise model for underwater channel $N(f)$ including turbulence, shipping, waves, and thermal noise follow overall power spectral density as in Eq. 7. The shipping factor and speed of wind causing noises are $s = 0.2$ and $w = 5m/s$, respectively following to the typical underwater simulation model in [16].

At the MAC layer, we adapt the behavior of IEEE 802.11 Ad Hoc mode for medium access control protocol in the underwater environment, as mentioned in [4], [5]. However, all the parameters of 802.11 are tuned to satisfy the characteristics of physical underwater acoustic channel. Besides, the exponential backoff algorithm is utilized in 802.11 MAC to resolve contention between different nodes which need to access channel. Each node is enabled to transmit its data when the backoff timer exceeds, which is a random number of slots uniformly chosen in the interval $(0, CW-1)$ (referred as Contention Window) before accessing to the medium. The slot time is set to 20 μs for 802.11 DSSS PHY. However, regarding to the distance between nodes and the high propagation delay in this model, we choose the slot time to be 0.18s. Furthermore, contention windows assigned CW_{min} at the first transmission and then doubled at each retransmission up to CW_{max} need to be changed to improve the low channel utilization due to backoff contention mechanism. The CW_{min} and CW_{max} are set to 4 and 32, respectively, instead of 32 and 1024 as in terrestrial 802.11 DSSS [5]. Source nodes generate messages with the packet length of 200-byte according to the constant bit rate (CBR) with different values of packet inter-arrival time (packets per second). The maximum transmission power is 0.5 W with an initial energy level of 1 kilojoule (kJ).

B. Numerical Results and Analysis

The proposed scheme is compared with shortest path first (SPF) routing scheme based on the minimum number of hops to reach the sink and the proposed scheme but without cooperative diversity under three metrics: average energy consumption, packet delivery ratio, and end-to-end delay.

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

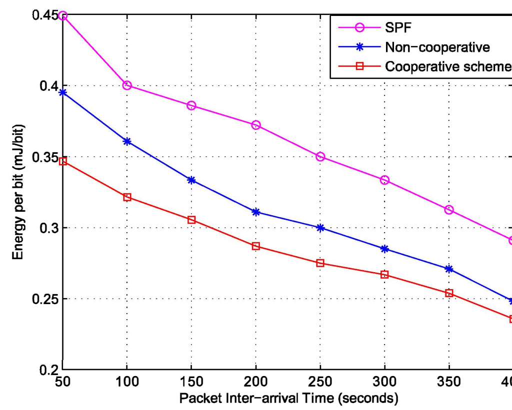

Fig. 4. Average energy per bit successfully received at the sink.

2) Packet delivery ratio: We evaluated the effects of the cooperative transmission model to the underwater link in order to reduce the packet loss caused by signal degradation over the medium channel. When the packet inter-arrival time is small, the higher traffic is sent from source nodes. This increases packet collision leading a lower packet delivery ratio. Fig. 5 indicates that the cooperative scheme achieves the higher packet delivery ratio as compared to the other schemes. Transmission without the channel estimation in SPF causes higher packet loss. Moreover, traffic focusing on the paths with the minimum number of hops can cause more collisions and packet delay as shown in Fig. 6. Cooperative scheme improves the possibility of receiving packets successfully by forwarding packets on multiple paths and combining at receiver node.

3) The impact of end-to-end delay on the underwater channel: The propagation delay in UW channel causes high latency for packets. Average end-to-end delay with respect to three schemes, is shown in Fig. 6 when packet inter-arrival time is set to be 150 seconds. The SPF forwards packets with minimum hops but the low quality channel can increase packet loss at the destination, therefore the packets need to be retransmitted. This intensifies the end-to-end packet delay. While two schemes are based on channel estimation, the packet is forwarded with the higher reliability, leading to lower retransmissions, especially in the case of the cooperative scheme. The packet, thus, reaches the sink with a lower delay.

V. CONCLUSIONS

This paper presented an adaptive scheme of cooperative communication originally developed for terrestrial wireless

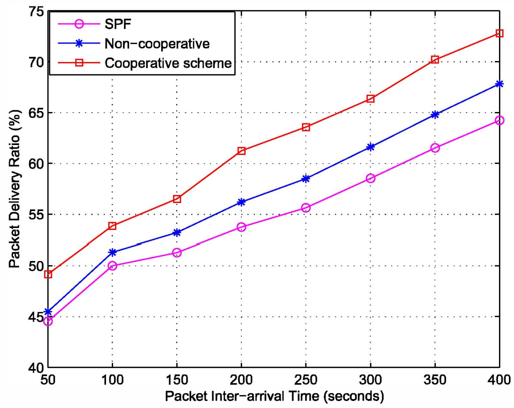

Fig. 5. Packet delivery ratio vs. time for different routing schemes.

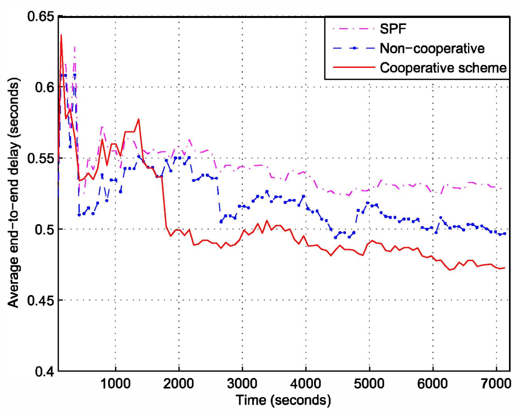

Fig. 6. Average end-to-end packet delay vs. time for different routing schemes.

networks to enhance reliability for communication link in underwater acoustic channel, where the propagation delay strictly affects to the diversity combination at the destination. The relay selection process considers the instantaneous link conditions and distance cost among surrounding nodes to successfully relay packets to the destination in a constrained environment as UW-ASN. Thoroughly, the paper combined multiple issues in design from the physical layer to the network layer. It showed that the distributed cooperative scheme with specific relay selection technique outperforms the traditional one-path communication in resource-constrained wireless networks without additional hardware requirement such as GPS system or multiple antenna arrays. Hence, the cooperative diversity scheme reduces the complexity at the physical layer and enhances the flexibility in implementation.

Further optimizations need for future research of UW-ASN including: (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) further analysis to the network capacity under interference and collision among the devices.

Acknowledgments

This research was financially supported by the Ministry of Education, Science Technology (MEST) and through the Human Resource Training Project for Regional Innovation 2013.

References

[1] D. Pompili and I. Akyildiz, "Overview of networking protocols for underwater wireless communications," *IEEE Communications Magazine*, vol. 47, no. 1, pp. 97 –102, jan 2009.

[2] W. Zhang, M. Stojanovic, and U. Mitra, "Analysis of a simple multihop underwater acoustic network," in *Proceedings of the third ACM international workshop on Underwater Networks*, ser. WuWNeT, 2008, pp. 3–10.

[3] A. Stefanov and M. Stojanovic, "Design and performance analysis of underwater acoustic networks," *IEEE Journal on Selected Areas in Communications*, vol. 29, no. 10, pp. 2012 –2021, dec 2011.

[4] D. Pompili, T. Melodia, and I. Akyildiz, "Distributed routing algorithms for underwater acoustic sensor networks," *IEEE Transactions on Wireless Communications*, vol. 9, no. 9, pp. 2934 –2944, sep 2010.

[5] D. Pompili, T. Melodia, and I. F. Akyildiz, "Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks," in *Proceedings of the 12th annual international conference on Mobile computing and networking*, ser. MobiCom, 2006, pp. 298–309.

[6] J. Laneman, D. Tse, and G. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Transactions on Information Theory*, vol. 50, no. 12, pp. 3062 – 3080, dec 2004.

[7] C. W. Ahn and J.-H. Lee, "Wireless cooperative communication: a survey," in *Proceedings of the 5th International Conference on Ubiquitous Information Management and Communication*, ser. ICUIMC, 2011, pp. 78:1–78:6.

[8] A. Bletsas, A. Khisti, D. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE Journal on Selected Areas in Communications*, vol. 24, no. 3, pp. 659 – 672, mar 2006.

[9] Z. Han, Y. Sun, and H. Shi, "Cooperative transmission for underwater acoustic communications," in *IEEE International Conference on Communications*, may 2008, pp. 2028 –2032.

[10] M. Vajapeyam, S. Vedantam, U. Mitra, J. Preisig, and M. Stojanovic, "Distributed space-time cooperative schemes for underwater acoustic communications," *IEEE Journal of Oceanic Engineering*, vol. 33, no. 4, pp. 489 –501, oct 2008.

[11] R. J. Urick, *Principles of underwater sound for engineers*. McGraw-Hill, 1967.

[12] L. Berkhovskikh and Y. Lysanov, *Fundamentals of Ocean Acoustics*. Springer, 1982.

[13] D. Brennan, "Linear diversity combining techniques," *Proceedings of the IEEE*, vol. 91, no. 2, pp. 331 – 356, feb 2003.

[14] Z. Zhou, S. Zhou, J.-H. Cui, and S. Cui, "Energy-efficient cooperative communication based on power control and selective single-relay in wireless sensor networks," *IEEE Transactions on Wireless Communications*, vol. 7, no. 8, pp. 3066 –3078, aug 2008.

[15] M. U. Ilyas, M. Kim, and H. Radha, "On enabling cooperative communication and diversity combination in ieee 802.15.4 wireless networks using off-the-shelf sensor motes," *Wireless Networks*, vol. 17, pp. 1173–1189, 2011.

[16] J. Xu, K. Li, G. Min, K. Lin, and W. Qu, "Energy-efficient tree-based multi-path power control for underwater sensor networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. PP, p. 1, 2012.