Channel-Aware Cooperative Routing in Underwater Acoustic Sensor Networks

Hoa Tran-Dang and Dong-Seong Kim

Abstract: **This paper proposes cooperative routing algorithms to improve the performance of underwater acoustic sensor networks (UW-ASNs). With the consideration of the poor acoustic link quality, a cross-layer design of physical layer and network layer is described for selecting simultaneously routing relays (RR) for forwarding data on routing paths and cooperative relays (CR) for one-hop cooperative communications. In the networks, sources that have data to transmit independently selects their own relays (i.e., both RR and CR) among their neighbors based on their link quality indicators (i.e., signal-to-noise ratio (SNR), time of arrival (ToA)) and their physical distances represented by hop count (HC) to the destination. Exploiting packet receiving or overhearing in the networks, these parameters are averaged and updated frequently to adapt to the unreliable and varying characteristics of acoustic channel over the time. By this way, the "best" relays with the "best" estimated measurements are selected reliably. Our simulation results show that the proposed algorithms improve the network performance in terms of end-to-end delay, energy consumption and packet delivery ratio.**

Index Terms: **Cooperative transmission, cooperative routing, cross-layer design, energy consumption, packet delivery ratio, signal-to-noise ratio (SNR), underwater acoustic sensor networks (UW-ASN).**

I. INTRODUCTION

UNDERWATER acoustic sensor networks (UW-ASNs) have recently attracted scientist in many oceanographic applications, i.e., pollution monitoring and disaster preventions. However, underwater networks face some critical challenges such as severely limited available bandwidth, high bit error rates, limited battery power, multi-path fading, which needs more deeply researches to take up. Extensive researches have been conducted on acoustic channel modeling and physical layer transmission analysis [1]–[3], while networking protocols are investigated in [4], [5].

In UW-ASNs, it is unprofitable to deploy more than one antenna on wireless terminal for multiple-input multiple-output (MIMO) communication due to limitation of size, cost and energy reservation. To overcome such problem, cooperative communication taking advantage of broadcast nature of the wireless channel has been exploited to enhance link quality and reliability [6], [7]. In [8], Z. Han *et al.* studied cooperative transmission technique for underwater communication. Three cooperative strategies, i.e., amplify-and-forward, decode-and-forward, and estimate-and-forward are analyzed in terms of channel capacity. 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.* Reference [9] 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 networking perspective, data transmitted in multi-hop manner aims 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 (routing relay) in routing protocols can be optimized such that the optimal network performance (i.e., shortest end-to-end delay, minimum energy consumption or highest packet delivery ratio) can be obtained [10]. Depending 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 [11]. Meanwhile, according to the protocols proposed in [12], [13], the sensor nodes with the highest residual energy are assigned as relay nodes of routing paths.

In this paper, we propose a cross-layer design of physical layer and network layer for cooperative routing in the UW-ASNs. Accordingly, the combination of routing and cooperative transmission involve selecting simultaneously routing relays (RR) for forwarding data on routing paths and cooperative relays (CR) for one-hop cooperative communications. In our network, sources that have data to transmit independently selects their own relays (i.e., both RR and CR) among their neighbors based on their link quality indicators (i.e., signal-to-noise ratio (SNR), time of arrival (ToA)) and their physical distances represented by hop count (HC) to the destination. We improve our previous work [14] by proposing algorithms to se-

Manuscript received March 15, 2018; approved for publication by Di Wu, Division III Editor, October 16, 2018.

This research was financially supported by the MSIT (Ministry of Science, ICT), Korea, under the ITRC (Information Technology Research Center) support program (IITP-2018-2014-1-00639) supervised by the IITP (Institute for Information & communications Technology Promotion), and Priority Research Centers Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2018R1A6A1A03024003).

The authors are with the Department of ICT Convergence Engineering, Kumoh National Institute of Technology, email: {hoa.tran-dang, dskim}@kumoh.ac.kr.

D.-S. Kim is the corresponding author.

Digital Object Identifier: 10.1109/JCN.2019.000004

1229-2370/19/$10.00 © 2019 KICS

lect efficient relays characterized by good wireless channel condition and short distance to the destination.

The key contributions of paper are as follows:

1. Taking full of broadcast nature of wireless communication, the neighbor tables of nodes are updated frequently as they receive or overhear any packets. To obtain the energy efficiency of network, only neighbors with unreliable link quality are updated in the tables. In this way, neighbor information including neighbor nodes and network channel conditions is estimated more accurately. Therefore, the efficient relays are selected reliably.
2. We propose two policies to select the routing relay based on the channel capacity of links and the propagation delay of links respectively. Meanwhile, the cooperative relay with the minimum propagation delay to the routing relay is selected to reduce the spread delay in the acoustic communication.
3. We compare the proposed cooperative routing schemes with some existing schemes to highlight the network performance in terms of average end-to-end delay, packet delivery ratio and energy consumption.

The rest of this paper is organized as follows. Section II introduces the specific characteristics of acoustic channel under the underwater environment. The proposed scheme is described in Section III. Section IV presents the performance evaluation. Finally, a conclusion and future directions are drawn in Section V.

II. UNDERWATER ACOUSTIC CHANEL MODEL

A. Attenuation and Propagation Delay

Comparing to electromagnetic terrestrial channels, the propagation delay of sound in underwater environment is five orders of magnitude higher than in radio frequency (RF) terrestrial channels, which is due to the low speed of sound ($c = 1500$ m/s). Meanwhile, the attenuation caused by two main factors, i.e., high environment noise and medium absorption is given by [15], [16]:

$$B_T(\gamma, f) = \gamma^{s_c} a_s(f)^{\alpha}, \tag{1}$$

where s_c is the spreading coefficient, γ being distance (km) between the source and the destination, f being operation frequency of acoustic signal (kHz) and a_s being absorption coefficient. The frequency-dependent absorption coefficient $a_s(f)$ is calculated from following equation [15], [17]:

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

B. Noise Model

In UW environment, there exists the isotropic noise level consisting of turbulence noise (N_{tu}) (valid for $1\,\text{Hz} < f < 10\,\text{Hz}$), far shipping traffic noise (N_{sh}), sea state noise (valid for $300\,\text{Hz} < f < 100\,\text{kHz}$), molecular agitation noise (valid from $100\,\text{kHz}$ to $1\,\text{MHz}$), which can be modeled by the Gaussian statistics and the power spectral density of those ambient noises, as presented in [17].

Underwater communication is affected by various 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 dB re μ Pa per Hz), as described in [15], [17]:

$$10\log N_{tu}(f) = 17 - 30\log(f), \tag{3}$$

$$10\log N_{sh}(f) = 40 + 20(s_{af} - 0.5) + 26\log(f) - 60\log(f + 0.03), \tag{4}$$

$$10\log N_{ss}(f) = 50 + 7.5\sqrt{\omega_s} + 20\log(f) - 40\log(f + 0.4), \tag{5}$$

$$10\log N_{ma}(f) = -17 + 20\log(f), \tag{6}$$

where the shipping activity factor s_{af} is in the range $[0 : 1]$ and ω_s (m/s) is the wind speed. Therefore, the overall ambient noise is given by:

$$N(f) = N_{tu}(f) + N_{sh}(f) + N_{ss}(f) + N_{ma}(f). \tag{7}$$

C. Acoustic Channel Capacity

For the networks deployed in a shallow regions, the dominant factor impacting strongly on the acoustic networking is ambient noise. In addition, low data generation rate of acoustic sensor nodes contributes to reductions of interferences. Therefore, the interference can be neglected in the studied system model. In this way, the acoustic channel capacity is dependent on the SNR, which can be calculated as:

$$SNR(\gamma, f) = \frac{P/B_T(\gamma, f)}{N(f)B}, \tag{8}$$

where P is transmission power in Watt, B being bandwidth in Hz. The channel capacity $C(f, \gamma)$ (bits/s) which is the tight upper bound on the rate that information can be reliably transmitted over a communication channel, follows the Shannon-Harley theorem [18]:

$$C(\gamma, f) = B\log_2(1 + SNR(\gamma, f)). \tag{9}$$

According to the theorem of Shannon given in [19], [20], the received signal can be decoded successfully at the receiver when the channel capacity is greater than or equal to the transmission rate. Thus, in order to obtain a high probability of data transmission success in the unreliable communication of acoustic channel, the transmission rate of acoustic link (R_T) should be satisfied:

$$R_T \leq C(\gamma, f). \tag{10}$$

In other word, the obtained $SNR(\gamma, f)$ should be greater than the threshold SNR_T for all the acoustic links ($SNR(\gamma, f) \geq SNR_T$). In this paper, we consider this transmission rate threshold as a condition in assessing the quality of an incoming wireless signal. This method has the advantage of link efficiency approximation without requiring any complex coding, detection and decoding.

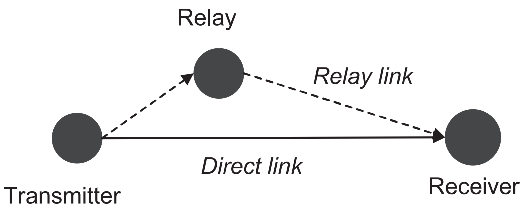

Fig. 1. Cooperative transmission scheme uses a relay node to forward data of a transmitter to a receiver.

D. Network Topology

In general, underwater environment is strongly affected by ambient noise and multi-path fading. In particular, sensor nodes in this work are deployed in a shallow ocean less than 100 m deep in order to monitor and detect events in many applications, i.e., offshore exploration, disaster prevention, assisted navigation and tactical surveillance. Therefore, the acoustic communication links are characterized by high dynamic reliability. This paper models the signal propagation following Rayleigh distribution as these applications are usually deployed in water region. The proposed algorithm takes advantage of the broadcast nature of wireless communication to increase the reliability of the UW wireless communication.

III. UNDERWATER ACOUSTIC COOPERATIVE ROUTING MODEL

A. Single Relay Cooperative Transmission

We consider a simple cooperative transmission model in wireless network that consists of one transmitter, one relay and one receiver, as depicted in Fig. 1.

Adopting the TDMA-based channel access scheme, the single cooperation transmission is accomplished within two time slots. In the first time slot, the transmitter transmits the data packet to the receiver by broadcast mode. The relay, in the second time slot, tries to decode, re-encode and transmit that packet which it overheard in the first time slot to the receiver [3]. This technique, called decode-and-forward protocol, is widely used in cooperative transmission to significantly eliminate noise in the forwarding phase [21]. The receiver combines the two signals from the direct link and relay link by the diversity-combining techniques to enhance the reception quality.

B. Cooperative Routing in Multi-hop UW-ASNs

This paper considers an UW-ASNs consisting of a set of sensors and a predefined destination (sink). The sensors deployed randomly in an underwater region sense frequently the surrounding environment and then transmit the sensed data to the destination by multi-hop fashion. As combined with the cooperative transmission scheme, data transmission from sources to the destination involves both types of nodes: relay nodes of routing paths (routing relays) and relay nodes of one-hop cooperative communication (cooperative relays). Fig. 2 illustrates an example of the UW-ASNs deploying the cooperative routing scheme to send the sensed data from one source (S) to the destination (D).

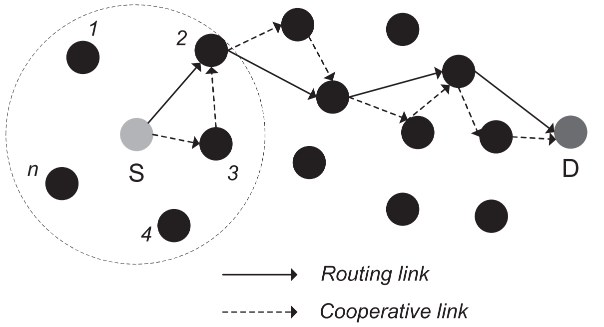

Fig. 2. Cooperative routing in multi-hop UW-ASNs.

Table 1. Summary of notations and symbols.

Notation	Representation of the symbol or symbol
$\mathcal{NB}(i)$	The neighbor list of node i
$\mathcal{NB}(i,j)$	The joint neighbor list of two nodes i & j; $\mathcal{NB}(i,j) = \mathcal{NB}(i) \cap \mathcal{NB}(j)$
$\mathcal{PR}(i)$	The list of potential relays of node i
$RR(i)$	The selected routing relay of node i
$CR(i)$	The selected cooperative relay of node i
$i \to j$	The link of data transmission from node i to node j
$SNR^{stored}_{(i \to j)}$	The stored SNR value of the link $i \to j$
$SNR^{new}_{(i \to j)}$	The new SNR value of the link $i \to j$ after a packet received
$SNR^{updated}_{(i \to j)}$	The updated SNR value of the link $i \to j$
$ToA^{stored}_{(i \to j)}$	The stored ToA value of the link $i \to j$
$ToA^{new}_{(i \to j)}$	The new ToA value of the link $i \to j$ after a packet received
$ToA^{updated}_{(i \to j)}$	The new ToA value of the link $i \to j$
HC_i	The number of hops from node i to the destination

For any node that needs to transmit the data, it independently selects the both types of nodes among its neighbors according to certain policies based on collected information of its neighbors. These selection policies are described in next sections. For clarity of the proposition description, the important variables and notations are listed in Table 1.

In this paper, delivering data from sources to the destination using cooperative routing involves four essential phases: neighbor table updating, RCS/CTS message exchange, relay selection, data packet transmission and acknowledgment, which are described sequentially as follows:

B.1 Neighbor Table Updating

Since selecting the relays plays a decisive role in the efficiency of data transmission in the networks, the source nodes rely on information of their neighbors to determine the proper relays. In this paper, via packet exchange, the nodes acquire the information characterizing the channel conditions of the network and store it in their corresponding neighbor tables. At the initialization period, the predefined destination broadcasts advertisement packets (ADV) to all the sensor nodes. Sensor nodes receiving such packets continue to broadcast them to their neighbors. Simultaneously, taking advantage of receiving the ADV packet, a node can gather significant information of its neighbors as follows:

1. SNR values on the links between it and its neighbors.
2. Number of hops (HC) from it to the destination. A "Hop Count" field contained in the ADV packet increases as that packet has passed. Based on this parameter, it should for-

Table 2. Neighbor table of source node s.

$\mathcal{NB}(s)$	i	j	k
HC	HC_i	HC_j	HC_k
ToA	$ToA_{(i\to s)}$	$ToA_{(j\to s)}$	$ToA_{(k\to s)}$
SNR	$SNR_{(i\to s)}$	$SNR_{(j\to s)}$	$SNR_{(k\to s)}$

ward its data packet to the neighbor which has the smallest number of hops to the destination. By this way, the data can be delivered on the shortest paths from sources to the destination [22].

3. ToA indicating the packet travel time periods. A "TimeStamp" field included in the ADV packet is used estimate the parameter. Since no position information of nodes is available, the ToA values can be used to represent the relative physical distance between nodes.

Table 2 illustrates a typical neighbor table stored and maintained at node s frequently.

After the initialization process is accomplished, the network status is stable. However the ADV packets are still broacasted periodically to keep the neighbor tables of nodes in the network up to date after a pre-defined period of time that is set to be 100 s. Unlike terrestrial radio communication, SNR and ToA parameters in underwater environment are always out-of-date due to the long propagation delay and fast varying acoustic channel [3]. Thus, in order to cope with the unreliable and dynamic characteristics of acoustic channel, we propose to update the neighbor tables of the nodes as Algorithm 1 whenever they receive any packets intended to them or even overhear packets transmitted by their neighbors. In this case, these packets are required to contain the two fields: "Hop Count", "TimeStamp". Accordingly, when a new packet is received at a certain node, it can estimate the new values of SNR and ToA that then are averaged with the values stored in the neighbor tables. For generality, the updated values of such parameters can be calculated as (11), (12), respectively.

$$SNR^{updated}_{(i\to j)} = (1-a) \times SNR^{stored}_{(i\to j)} + a \times SNR^{new}_{(i\to j)}, \quad (11)$$

$$ToA^{updated}_{(i\to j)} = (1-a) \times ToA^{stored}_{(i\to j)} + a \times ToA^{new}_{(i\to j)}, \quad (12)$$

where a $(0 < a < 1)$ is the stability factor indicating the rate of changing the network and underwater environment. The changing rate is characterized by how much the values (i.e., SNR, ToA) of older transmission vary. For instance, a higher a could be used for highly variable underwater channels, as it discounts older transmissions faster.

Note that, the updated ToA values take into account the history transmissions of their links. In other words, the field "TimeStamp" is maintained from a packet generated from the source until it is successfully received at the next hop node. In other word, through using "TimeStamp", the ToA of a link can be calculated as follow: $ToA = current\ clock\ time\ of\ receivers$ - $"TimeStamp"\ of\ received\ packet$. With such calculation method, the paper assumes that the time clocks of nodes are synchronized. Given that each packet is allowed to be retransmitted in two times, the ToA values of links with more unsuccessful transmissions get higher over time. This method enables the routing scheme to select reliable links with less unsuccessful transmissions for forwarding data.

Algorithm 1: Updating neighbor table of node s.

Input : Received packets
Output: Neighbor table of node s
When node s receives any packet sent by node i ;
if $i \in \mathcal{NB}(s)$ **then**
  if $HC_s \geq HC_i + 1$ **then**
    $HC_s \leftarrow HC_i + 1$;
  end
  Updating $SNR_{(i\to s)}$ as (11) ;
  Updating $ToA_{(i\to s)}$ as (12) ;
else
  $\mathcal{NB}(s) \leftarrow i$;
  $HC_s \leftarrow HC_i + 1$;
  $ToA_{(i\to s)} \leftarrow ToA^{new}_{(i\to s)}$;
  $SNR_{(i\to s)} \leftarrow SNR^{new}_{(i\to s)}$;
end

This updating procedure may consume additional energy for receiving and processing the packets, however, the channel conditions of acoustic links between nodes and their neighbors can be estimated more accurately over the time. 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) [23]. Thus, the better trade-off in terms of energy efficiency can be obtained since retransmission of data packets is reduced on good quality links selected based on the up-to-dated link channel conditions. Furthermore, due to packet errors or packet collisions in the network the proposed procedure allows nodes to avoid their unexplored neighbors, which specially could be selected as efficient relays.

B.2 RTS/CTS Message Exchange

When the source node has data to transmit, it broadcasts the RTS packet to its neighbors. At receiver side, neighbors receiving the packets perform the neighbor table updating followed by Algorithm 1. Based on the updated information in the neighbor tables, neighbor nodes can nominate themselves as potential candidates for relays. In this paper, a nominated potential relay i of a source node s must have two following characteristics: (1) $SNR_{(s\to i)} \geq SNR_T$; (2) $HC_i \leq HC_s$. Accordingly, the first condition enables data transmission on the link $s \to i$ with high probability of success given the threshold data rate R_T. Meanwhile, with the second condition, the source s forwards greedily its data to the relay, which is nearer physically to the destination. Upon holding the criteria, only the potential relays inform their corresponding sources by transmitting CTS packets. The procedure of RTS/CTS message exchange is described in Fig. 3.

Note that the RTS/CTS packet length is assumed to be small compared to data packet length. Thus, the energy consumption overhead is negligible. In practical scenario, the sensor nodes are

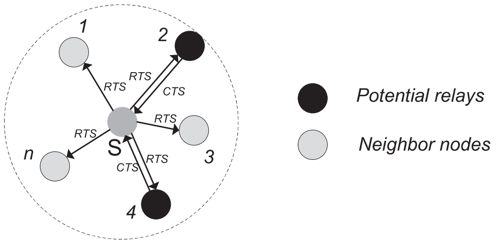

Fig. 3. RTS and CTS packet exchange between source node and neighbor nodes. Only potential relays reply CTS packets.

Algorithm 2: Listing potential relay candidates.

Input : $\mathcal{NB}(s)$, received CTS packets
Output: $\mathcal{PR}(s)$
When source s receives a CTS packet sent from neighbor i;
if $\{SNR_{(s \to i)}, SNR_{(i \to s)}\} \geq SNR_T$ & $HC_s \geq HC_i$ **then**
  $\mathcal{PR}(s) \leftarrow i$;
end

randomly deployed in a wide area. Therefore, multiple sources that have information to transmit are inevitable. As a result, packet collisions occur since many potential candidates of relays may need to send CTS packet at the same time. To overcome such aforementioned shortcoming, we assume that the sensing rate of each node is small.

B.3 Relay Section

After finishing RTS/CTS phase, the source node receives the CTS packets and has full knowledge of its potential relays. Due to unreliability and dynamic of acoustic channel, the potential relay candidates of the source should be shortlisted in taking into account asymmetric characteristic of acoustic links, i.e., $ToA_{(i \to j)} \neq ToA_{(j \to i)}$, $SNR_{(i \to j)} \neq SNR_{(j \to i)}$. Accordingly, neighbors that form good quality communication links with their source in the both directions are added to the shortlist of potential relays. In addition, the potential relays that are nearer to the destination than the source allow data packets to be routed on the shortest path greedily. Otherwise, they are excluded from the list of candidate relays. This shortlisting process is described in Algorithm 2.

This criteria of shortlisting potential relay aims to constrain the number of nodes joining the relay selection process. Thus, the computational complexity and delay can be significantly reduced. After all the candidates are checked, the source node obtains the list of potential relay nodes, which satisfies distance and channel capacity conditions. IN this paper, we propose two policies based on SNR and ToA values to select the "best" routing relay as described in Algorithm 3 and Algorithm 4, respectively. For the SNR-based selection, the potential relay with the maximum SNR value is selected as the "best" routing relay since it allows the data reception with the highest probability of success as well as the highest channel capacity obtained. Meanwhile, selecting the potential relay with the minimum travel time of packet propagation, the source could greedily decrease the end-to-end delay on the routing path.

After choosing the "best" routing relay, the source s selects

Algorithm 3: Select the "best" routing relay node based on SNR.

Input : $\mathcal{PR}(s)$
Output: $RR(s)$
for $i \in \mathcal{PR}(s)$ **do**
  if $SNR_{(s \to i)} = max\{SNR_{(s \to i)}\}$ **then**
    $RR(s) \leftarrow i$;
  end
end

Algorithm 4: Select the "best" routing relay node based on TOA.

Input : $\mathcal{PR}(s)$
Output: $RR(s)$
for $i \in \mathcal{PR}(s)$ **do**
  if $ToA_{(s \to i)} = min\{ToA_{(s \to i)}\}$ **then**
    $RR(i) \leftarrow i$;
  end
end

Algorithm 5: Select the "best" cooperative relay node.

Input : $\mathcal{NB}(s)$,$\mathcal{NB}(RR(s))$, $\mathcal{PR}(s)$
Output: $CR(s)$
for $i \in \mathcal{NB}(s) \cap \mathcal{NB}(RR(s)) \cap \mathcal{PR}(s)$ **do**
  if $ToA_{(i \to RR(s))} = min\{ToA_{(i \to RR(s))}\}$ **then**
    $CR(s) \leftarrow i$;
  end
end

the "best" cooperative routing that satisfies two following conditions: (1) It belongs to the intersection of three sets: $\mathcal{NB}(s)$, $\mathcal{NB}(RR(s))$ and $\mathcal{PR}(s)$; (2) The ToA value of the link between it and the selected routing relay is minimum as shown in Algorithm 5.

Since all the nodes of network are assumed to have the same power transmission, thus the same communication range, the first condition guarantees that the selected cooperating relay can overhear the packet transmitted from the source and then forwards it to the selected routing relay. Because the source independently assigns its routing relay as well as cooperative relay, it requires to be aware of the information about neighbors of its routing relay. To deal with such issue, the neighbor tables of the potential relays are inserted in the CTS packets. By this way, upon receiving those packets, the source can choose the "best" cooperative routing for it. The second condition is adopted from the investigation in the work [8] which indicated that the cooperative relay node should locate close to the direct transmission path to reduce the delay spread of the multi-path propagation. Fig. 4 illustrates an example to select the "best" CR for the source s.

Since GPS or localization information of nodes are not considered in this paper, the average ToA values can be translated to be the relative locations between the routing relay and the potential cooperative relays. In other words, the smaller value of

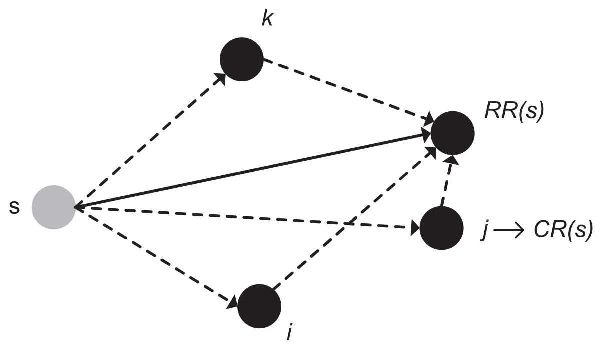

Fig. 4. The best CR j is selected for the source s among the potential CR nodes (i, j, k).

Table 3. Simulation Parameters.

Parameter	Parameter's value
Shipping activity factor	0.2
Wind Speed	$5\,\mathrm{m/s}$
Frequency	$30\,\mathrm{kHz}$
Speed of sound	$1500\,\mathrm{m/s}$
Transmission range	$100\,\mathrm{m}$
Transmission power	$0.5\,\mathrm{W}$
MAC protocol	IEEE 802.11
Packet Length (L)	200 bytes
Data rate (R)	$10\,\mathrm{Kbps}$
Slot time	$0.2\,\mathrm{s}$
$CW_{\min}$	4
$CW_{\max}$	32

ToA is, the closer the potential cooperative relay is to the routing relay.

B.4 Data Packet Transmission

In the packet transmission phase, the source first directly transmits the data packet to its selected routing relay. The data packet includes the identification numbers of two nodes assigned as routing relay and cooperative relay from the relay selection process. Upon receiving the packet, neighbor nodes can perform their corresponding tasks. Accordingly, the selected routing relay waits for receiving the packet transmitted from the cooperative relay in the second slot for joint decoding. Meanwhile, the other nodes, first, exploit the packets overheard to update their neighbor tables and then will immediately drop the message in order to reduce energy consumption and their own storage resources.

At the receiver side, if the received packet can be decoded successfully, an acknowledgment packet (ACK) packet is broadcasted to notify that the selected cooperative relay do not need to transmit the packet. In this way, the network performance can be improved in term of energy efficiency and delay as well.

To improve the reliability of data transmission, a retransmission mechanism is deployed. For any transmitter-receiver data transmission, the transmitter will retransmit the packet in two following cases:

1. After a timeout period set at the transmitter expires, if no ACK is received, the transmitter retransmits the data packet.
2. When the receivers decode the received packet unsuccessfully, it will send a negative acknowledgment (NACK) packet to request the retransmission. All received packets are assumed to be error if their payload are not decoded successfully. Meanwhile the header fields including transmitter IDs are not damaged in the communication. A field no_reTx denoting number of allowable retransmissions is included in the NACK packet. Such value is updated by the receiver to assign the retransmission role for the source and the selected CR. Accordingly, no_reTx is initialized to be 0. For the first unsuccessful transmission, no_reTx increases by 1. In this case, the selected CR is responsible for resending the packet if it receives the first NACK. Meanwhile, if the second NACK is received (i.e., $no\_reTx = 2$), the source retransmits the data packet. By exploiting the retransmission of the CR, energy consumption of nodes in the network would be balanced.

In the all two cases, the maximum number of retransmissions is set to two, after that the packet will be dropped and the next data packet will be proceeded. Moreover, the network then has to establish an alternative route since the continuous failure of data communication indicates a long-term breakage of the link (e.g., topology change because of node movement, etc.).

IV. PERFORMANCE EVALUATION

A. *Simulation Scenarios and Settings*

This section describes the model configuration of the considered networks to simulate in OPNET Modeler (version 16.0). In this paper, the homogeneous network consists of 100 acoustic sensor nodes deployed randomly and uniformly in a 3D space of shallow underwater environment ($500 \times 500 \times 100\ \mathrm{m}^3$) as source nodes and a sink (destination) is placed on the surface of region to collect the data sent from the sources. We assume that the environment change is stable. That means that the values ToA and SNR do not vary much, thus the stability factor a is set to 0.5. All the sensor nodes have the same limited radius transmission range of up to $100\,\mathrm{m}$ and operate at $30\,\mathrm{kHz}$. In addition, each node has an initial energy level of 1 kJ and the maximum transmission power of 0.5 W. Each data packet length (L) is fixed at 200 bytes, and the data rate (R) is chosen at 10 Kbps. Packet generation rate is varied to investigate the effect of traffic flow on the network performance. In this paper, this parameter is represented by the packet inter-arrival time defined as a time duration (in seconds) to generate a packet. Furthermore, the parameters of physical perspective are adjusted properly in the OPNET simulation model in order to coincide with underwater environment, i.e., propagation delay, background and noise model, which are presented in Table 3 based on references [4], [24].

Regarding to the network communication model, we adapt the typical IEEE 802.11 Ad Hoc network model for medium access control (MAC) mechanism [4] and [5]. Indeed, the related parameters of the standard communication are altered such as the simulation model reflects accurately the peculiar characteristics of acoustic communication, thus the simulation results are obtained reliably. We enable the built-in back-off algorithm following exponential distribution in IEEE 802.11 MAC in order to avoid network congestion. This mechanism allows every sensor node to detect packet collisions and to retransmits the packet when the back-off time is exceeded. Thus, each sender needs to wait in the interval before retransmission $(0, CW - 1)$, where CW stands for contention window. In addition, since each data packet transmission lasts at least 0.16 s (L/R) the slot time duration is set to be $0.20\ s$ instead of 20 μs in the IEEE 802.11 terrestrial wireless communications due to high propagation delay of acoustic signal in the underwater environment. Such slot time is sufficient for the time of data transmission, its ACK or NACK and the guard times. Specifically, we allow the sensor node to retransmit packet after $k \times CW_{\min}$ seconds where k is set to be 2. Thus, the retransmission is truncated when reaching timeout at $CW_{\max}$. We adjust the default value of $CW_{\min}$ and $CW_{\max}$ by 4 and 32, respectively. This is to improve the low channel utilization.

B. *Numerical Results and Analysis*

In order to evaluate the performance of network deploying the proposed cooperative routing schemes, we take following routing schemes to conduct simulations for comparative study.

- Routing schemes without cooperative communication:
  - The shortest path first routing (SPFR) scheme: This is the traditional routing without cooperative communication scheme, in which the routing relays are selected based only the hop count parameter such that the number of hops on the routing path is minimum.
  - SNR/ToA-based routing without cooperative communication (abbreviated as SNR/ToA-based-R): In these routing schemes, the potential relays with maximum SNR and minimum ToA are selected to become routing relays.
- The proposed cooperative routing schemes include SNR/ToA-based cooperative routing (abbreviated as SNR/ToA-based-CR).

The metrics used for comparative study include average end-to-end delay, packet delivery ratio, and energy consumption, which are investigated under the impact of number of sensor nodes, traffic and control packets.

B.1 Average End-to-End Delay

The average end-to-end delay required to deliver packets from any source-destination pair is calculated as summation of all delays of all received packets per the total number of received packets. Fig. 5 shows the average end-to-end delay of data packet transmission in the network obtained by the five routing schemes. The packet inter-arrival time is set to be 150 s and the delay is tracked over 7000 s of simulation.

Although, the data is greedily forwarded on the routing path with the minimum hop in the SPFR scheme, it incurs the highest end-to-end delay. This is due to unawareness of the acoustic link quality, packets that could be transmitted in low quality links are decoded unsuccessfully at the receivers. In combination with the packet collisions, more packets that must be retransmitted many times. As a result, the average end-to-end delay increases. Meanwhile, by learning the channel conditions of the network, the average delay is reduced considerably the four proposed routing scheme. Particularly, with the assistance of cooperative relays, the enhancement of reception quality, thus increase of successful reception ratio lowers necessary packet retransmission in the two cooperative routing schemes. Among them, the ToA-based-CR scheme delivers the data in the lowest average delay since the data is forwarded in the lowest and high quality links.

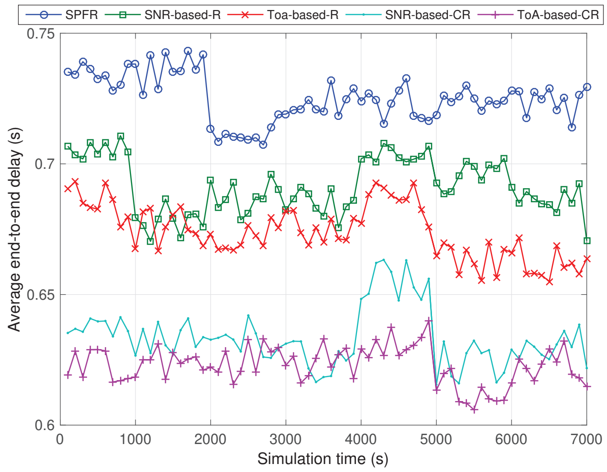

Fig. 5. Average end-to-end delay in the network over simulation time.

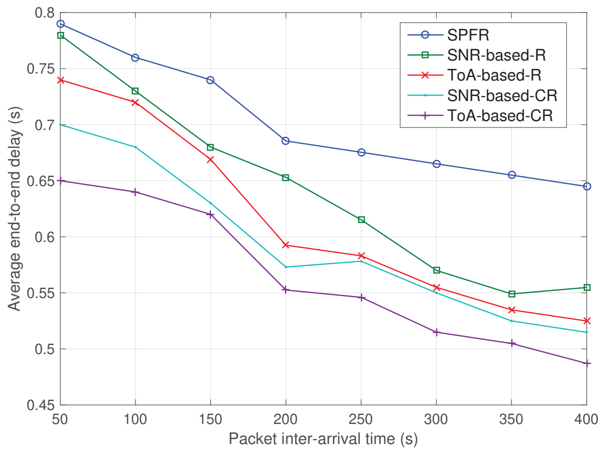

Fig. 6. Average end-to-end delay in the network verse traffic load.

To investigate the capability of data delivery of the routing schemes in the network with varying traffic load, Fig. 6 depicts the average end-to-end delay experienced by data packets successfully routed by the considered protocols.

All five schemes show good performance, especially each data packet transmission requires at least 0.8 s to travel to the destination on average. Decreasing the traffic load leads to improvement of the network performance, as expected. In other words, when the traffic increases each hop imposes longer delays because of the increased number of collisions and packet retransmissions. Although SPFR could deliver the data packet in the shortest path, the delay could not be reduced significantly. That is because the packets are transmitted in the links with channel unawareness. As a result, more packet errors as well as retransmissions impose longer delay of packets to the sink. ToA-based-CR shows the best delay performance since

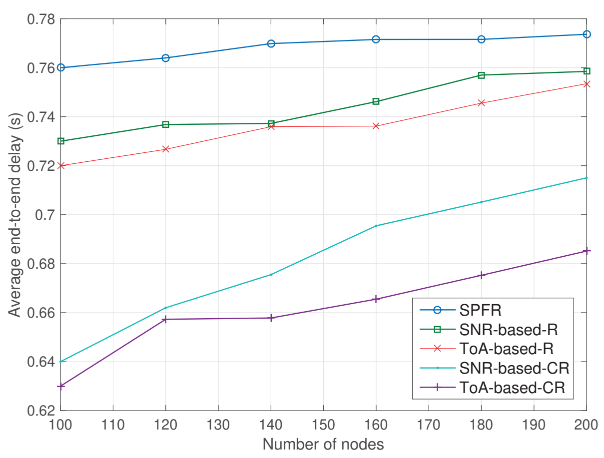

Fig. 7. Average end-to-end delay in the networks with different number of sensor nodes.

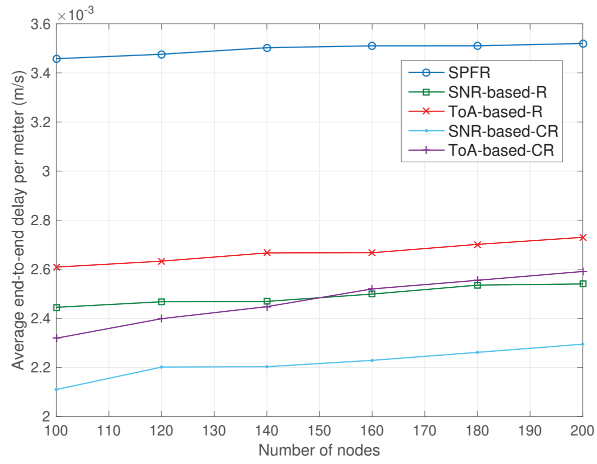

Fig. 8. Average end-to-end delay per meter in the networks with different number of sensor nodes.

the "best" relays are selected based on the "best" communication links in terms of minimum link delay. In addition, these robust links are maintained by neighboring updating mechanism. In this way, packet errors during transmission on such links are reduced considerably.

To investigate the impact of number of sensor nodes on the average end-to-end delay, five additional networks with 120, 140, 160, 180, and 200 nodes are simulated. Fig. 7 shows the average delay for the routing algorithms. As expected, increasing the density of nodes induces degraded performance of the network since more packet collisions results in more retransmissions of data packets.

Although the proposed cooperative routing protocols show the better average delay performance, they are impacted strongly by the density of nodes in the network. Concretely, the increasing rates of delay of such schemes are higher than that of the others due to more handshake phases of control packets exchanged among neighbor nodes. A remark from the results is that the proposed schemes can be applicable for medium scale networks.

The average end-to-end delay per meter experienced by data packets successfully delivered to the sink is shown in Fig. 8. Increasing number of nodes in the networks lead to longer delay for data packets sent to the destination. This happen even if the average number of hops traveled by each packet stays relative stable. The proposed schemes achieve the best delay per meter performance although they rely on the maximum hop counts from the sources to the sink on average to deliver the data packet. Fig. 9 illustrates the average hops that each data packet requires to reach the sink.

In addition, despite the absence of the handshake phase of control packet exchange and the minimum hops of travel the packets routed by the SPFR scheme require the longest delay per meter. Selecting the routing relay with the maximum SNR value leads to the fact that it will be close to its source. As a result, the average number of hops for data forwarding in the SNR-based routing schemes is maximum. Meanwhile, based on ToA values that take into account the historical transmission results (i.e., success or failure), neighbors being close to the source

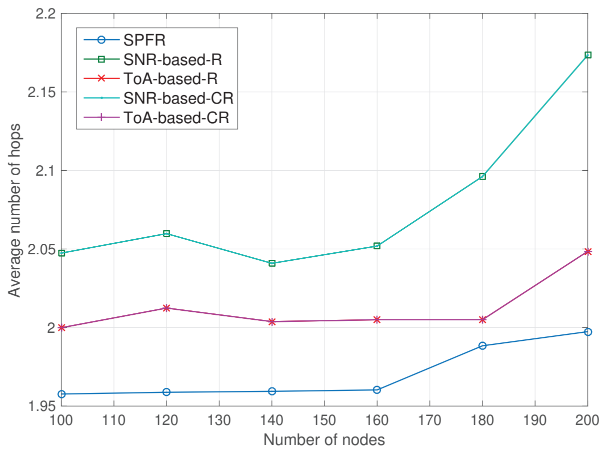

Fig. 9. Average end-to-end delay per meter in the networks with different number of sensor nodes.

do not guarantee the lower ToA. Indeed, increasing number of nodes leads to more neighbors for each source node and then more packet collisions as a consequence increases the ToA for those links. However, the outperformance of the SNR-based cooperative routing in terms of end-to-end delay (see Fig. 7) takes advantage in the lowest delay per meter regardless the maximum hops of packet delivery and handshake phase of control packet exchange.

Similarly, the average delay required to deliver packets successfully to the sink depends on the average distance between the sink and the sources. Fig. 10 illustrates such relationship. Six networks with random deployment of sensor nodes are conducted to measure the average delay of packets. Since all the sensor nodes are sources generating data packets, the average distances between the sink and the sources in the six networks are as 198.12, 256.32, 299.28, 346.22, 384.21, 421.28 m.

According to the simulation results, increasing the average distance to packet to travel from sources to the sink results in increasing the average end-to-end delay. Regarding the routing

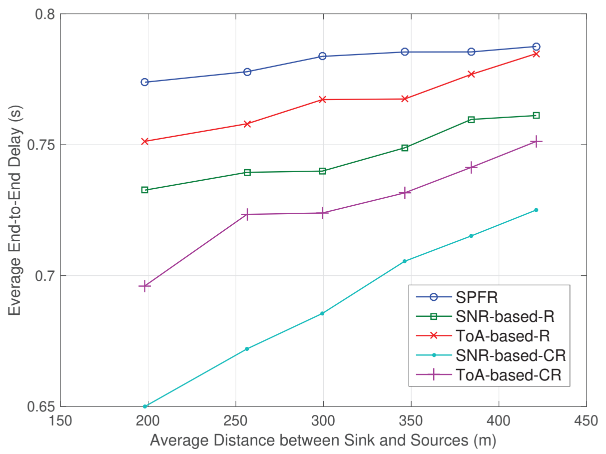

Fig. 10. Average end-to-end delay in the networks with average distances between sink and sources.

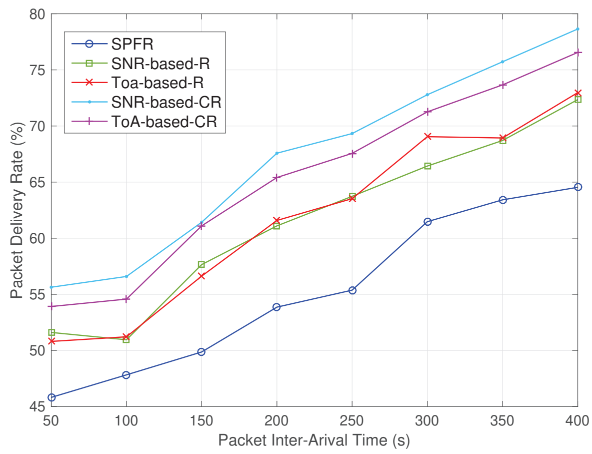

Fig. 12. Packet delivery ratio as a function of packet inter-arrival time.

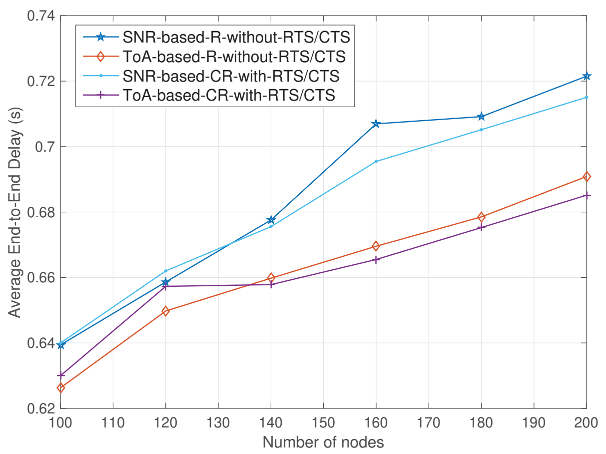

Fig. 11. Average end-to-end delay of the proposed cooperative routing protocols under impact of RTS/CTS packet exchange.

schemes, taking advantage of channel awareness, the introduced algorithms improve the packet delay. Especially, the cooperative routing solutions achieve the best outcome due to reducing the packet retransmissions.

In order to evaluate the impact of such handshake phase, Fig. 11 compares the average end-to-end delay of the proposed routing protocols with and without RTS/CTS packet exchange. The simulation result shows that RTS/CTS packet exchange deployed in the proposed algorithms can improve the delay for the denser network. One reason is that exploiting such control packets can estimate more correctly the status of acoustics links. In addition, in the networks with more populated nodes the handshake phase contributes to reduce collisions caused by hidden node problems in acoustics sensor networks. Furthermore, through the relay selection only limited potential candidates response CTS packets. As a result, data packets will be transmitted in selected routing relay with the best selected wireless link.

B.2 Packet Delivery Ratio

Due to strong absorption losses, packet delivery ratio is one of the important metrics to evaluate the proposed scheme in underwater scenario. In general, Fig. 12 shows that the packet delivery ratio of all schemes increases when packet inter-arrival increases (i.e., decreasing network traffic).

The low packet inter-arrival time leads to higher traffic sent from the source nodes. Therefore, it leads to low packet delivery ratio due to high probability of packet collisions and retransmissions as well as in a higher number of times the nodes sense the acoustic channel busy. SPFR algorithm achieves lowest packet delivery ratio as the algorithm focuses on the path with minimum number of hops, thus it causes packet collisions. On the other hand, the proposed scheme achieves the best performance in terms of packet delivery ratio because the cooperative scheme improves the possibility of successful packet reception. Specially, the ToA-based-CR scheme allows the network to obtain the highest packet delivery ratio since the data is transmitted on the "best" links characterized by the highest value of SNR. When the packet inter-arrival time is set to be 100 s, the SNR-based-CR delivers almost 80% of the generated data to the destination.

Similarly, the network performance in terms of PDR is degraded when the number of sensor nodes increase. More packet collisions caused multiple packet transmissions of neighbor nodes simultaneously are the primary reason for reducing the PDR. In addition, transmitting data packets in the links without channel awareness leads to error receptions. Such two problems are resolved effectively by the proposed algorithms. Accordingly, channel-aware data transmission approaches achieve better PDR. Particularly, cooperative routing enhances significantly this parameter due to improved success reception of the packets.

For the networks with different average distance between sink and sources, PDR measurements are varied correspondingly. Fig. 14 shows the impact of such distance on the PDR of networks. The graphs indicate the reduction of PDR as the average distances increase for all the simulated routing schemes. Among them, the channel-aware routings, especially ones with combi-

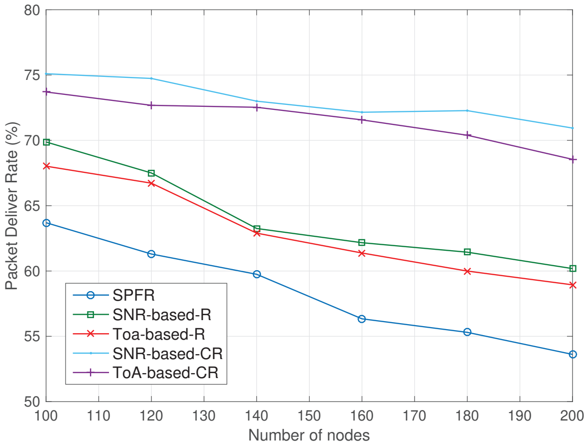

Fig. 13. Packet delivery ratio under the impact of number of network nodes.

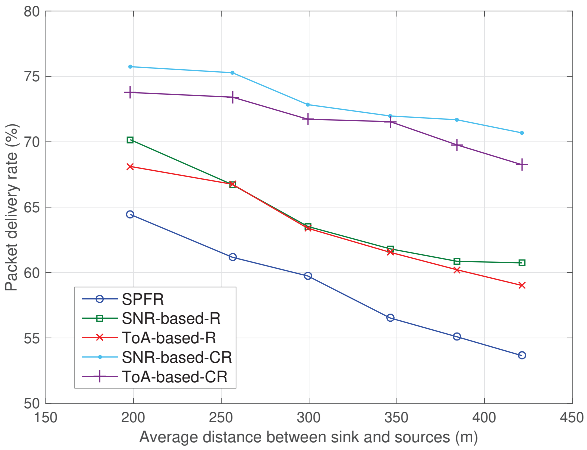

Fig. 14. Packet deliver ratios in the networks with average distances between sink and sources.

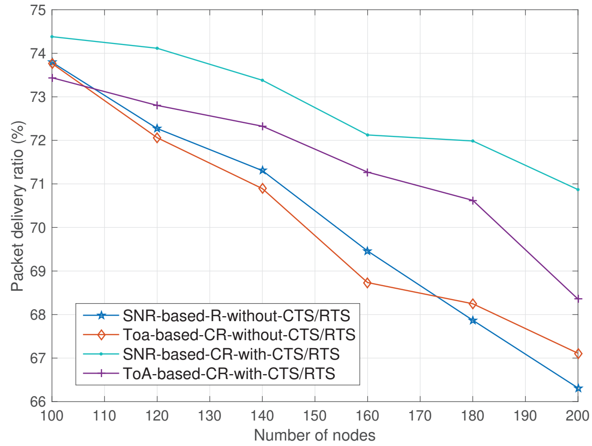

Fig. 15. Packet delivery ratio under the impact of RTS/CTS packet exchange.

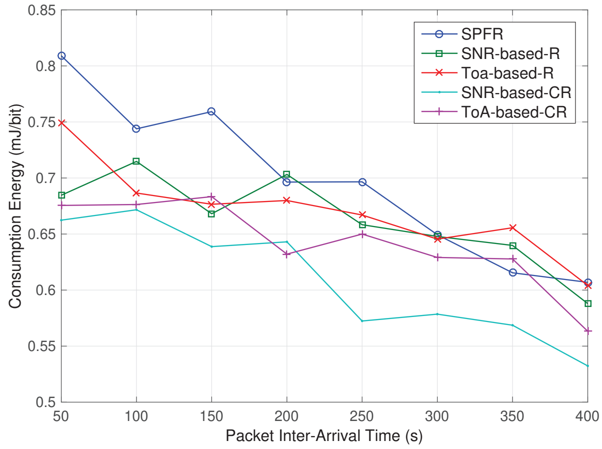

Fig. 16. Energy consumption as a function of packet inter-arrival time.

nation with cooperative communication remain higher ratio of packet delivery compared to the best effort routing with shortest path.

The channel awareness relies heavily on the packet exchange among nodes, especially short control packets. Fig. 15 illustrates the impact of the control packets (i.e., RTS/CTS) on the PDR of the network. As shown in the figure, the handshake phase for exchanging such packets is necessary to improve the PDR. The improvement is significant in the network with higher density of nodes.

B.3 Average Energy Consumption

Fig. 16 shows the average energy consumption of the mentioned routing schemes. The metric is defined as average energy required to transmit one bit from sources to the destination successfully.

The packet inter-arrival time is varied from 50 s to 400 s. As expected, increasing the traffic results in higher energy consumption for all the simulated routing schemes. The SPFR scheme consumes more energy than the other schemes since this algorithm does not take channel quality into account. Thus, it leads to multiple retransmissions in order to successfully send the data packet to the sink. The non-cooperative schemes requires lower energy cost than the SPFR since the channel estimation improves the received packet probability. Interestingly, the proposed cooperative scheme achieves best performance in terms of energy consumption because it can transmit through high quality multi-path when the channel quality changes.

Increasing the network density results in degraded performance in terms of energy consumption, as expected. Among the compared routing approaches, the SNR-based-CR use the least energy per bit for delivering the data packet. Besides transmitting the data in the reliable links, cooperative communication also contributes to the high probability of packet reception. Therefore, the retransmissions are reduced significantly.

Although the reliable links are estimated based on the control packet exchange, such handshake procedure would generate more overhead in the network. However, it still impacts positively on the network performance regarding to the consumption

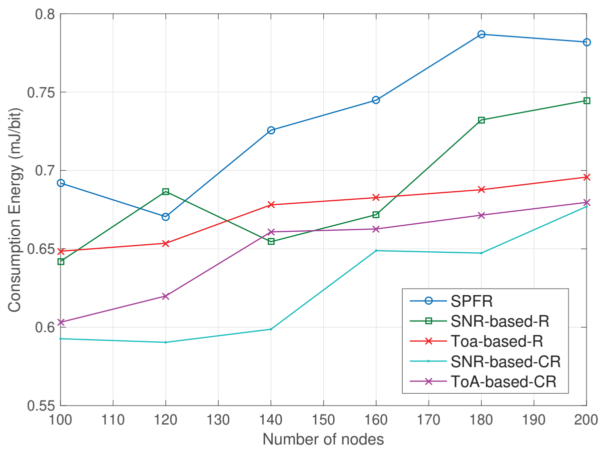

Fig. 17. Energy consumption as a function of network density.

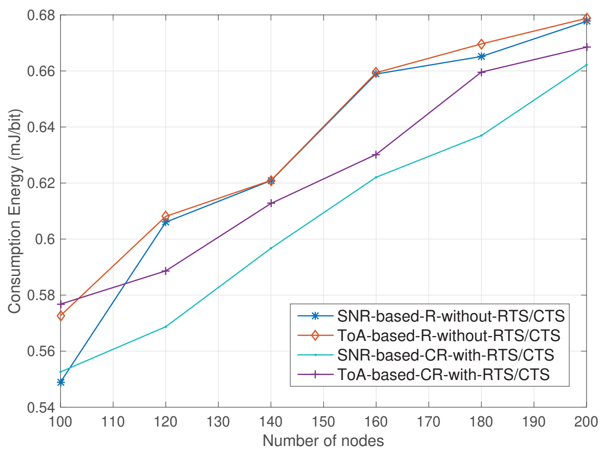

Fig. 18. Energy consumption under the impact of RTS/CTS packet exchange.

energy per bit. Fig. 18 illustrates the comparison of consumed energy for the proposed routing protocols with and without the usage of RTS/CTS control packets. The result shows that the short packets contributes to reduce the consumed energy significantly in the higher dense network, in which energy used for retransmission of packet is much higher than the control packet transmission.

V. CONCLUSIONS

In this paper, we proposed a cross-layer design of physical layer and network layer for routing algorithms, which aim to improve the performance of UW-ASNs under the effect of strong acoustic signal degradation and multi-path fading. By being awareness of the network channel conditions characterized by SNR and ToA values, the nodes shortlist the potential relays including routing relays and cooperative relays among neighbors based on the channel link quality. Particularly, exploiting packet receiving or overhearing in the networks, these parameters are averaged and updated frequently in the neighbor tables to adapt to the unreliable and dynamic characteristics of acoustic channel over the time. In this mechanism, the "best" relays with the "best" estimated measurements are selected reliably. Accordingly, the two cooperative routing schemes corresponding to the two routing relay selection algorithm (i.e., based on SNR and ToA, respectively) are proposed effectively enhance the successful reception packets at the receiver side. Meanwhile, the potential candidates with the minimum value of ToA between them and the selected routing relays are selected as the "best" cooperative relays to reduce the spread delay in the acoustic channel communication. Our simulation results show that the proposed method outperforms the well-known SPF algorithm and conventional non-cooperative scheme with regard to average end-to-end delay, packet delivery ratio and energy consumption.

We present a close examination including the physical layer, MAC layer and network layer. Specifically, our method is based on IEEE 802.11 ad hoc mode and "virtual" antenna array composing of multiple single antenna on each terminal. Thus, our method can be easily implemented in off-the-shelf devices without requiring additional hardware components, i.e., GPS. In future works, we will include rate and power allocation for both source and relay nodes. In addition, the interference-limited destination in which multiple interferences locate near the destination and isolate from other nodes will be analyzed to show the advantage of relay selection considering channel conditions in underwater sensor networks. Furthermore, the highly variable underwater environment will be taken into account to investigate the network performance under the proposed routing protocols.

REFERENCES

[1] W. Zhang, M. Stojanovic, and U. Mitra, "Analysis of a simple multihop underwater acoustic network," in *Proc. ACM WUWNet*, Sept. 2008, pp. 3–10.

[2] A. Stefanov and M. Stojanovic, "Design and performance analysis of underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 29, no. 10, pp. 2012–2021, Dec. 2011.

[3] C. W. Ahn and J.-H. Lee, "Wireless cooperative communication: A survey," in *Proc. ACM ICUIMC*, Feb. 2011, pp. 78:1–78:6.

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

[5] D. Pompili, T. Melodia, and I. F. Akyildiz, "Routing algorithms for delay-insensitive and delay-sensitive applications in underwater sensor networks," in *Proc. ACM MobiCom*, Sept. 2006, pp. 298–309.

[6] A. Bletsas, A. Khisti, D. P. Reed, and A. Lippman, "A simple cooperative diversity method based on network path selection," *IEEE J. Sel. Areas Commun.*, vol. 24, no. 3, pp. 659–672, Mar. 2006.

[7] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. Inf. Theory*, vol. 50, no. 12, pp. 3062–3080, Dec. 2004.

[8] Z. Han, Y. L. Sun, and H. Shi, "Cooperative transmission for underwater acoustic communications," in *Proc. IEEE ICC*, May 2008, pp. 2028–2032.

[9] M. Vajapeyam, U. Mitra, J. Preisig, and M. Stojanovic, "Distributed space-time cooperative schemes for underwater acoustic communications," in *Proc. OCEANS*, May 2007, pp. 1–8.

[10] G. Han, J. Jiang, N. Bao, L. Wan, and M. Guizani, "Routing protocols for underwater wireless sensor networks," *IEEE Commun. Mag.*, vol. 53, no. 11, pp. 72–78, Nov. 2015.

[11] S. Gopi, K. Govindan, D. Chander, U. B. Desai, and S. N. Merchant, "E-pulrp: Energy optimized path unaware layered routing protocol for underwater sensor networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 11, pp. 3391–3401, Nov. 2010.

[12] C.-J. Huang *et al.* "A power-efficient routing protocol for underwater wireless sensor networks," *Applied Soft Computing*, vol. 11, no. 2, pp. 2348 –

2355, 2011, the Impact of Soft Computing for the Progress of Artificial Intelligence.
[13] M. Zorzi, P. Casari, N. Baldo, and A. F. Harris, "Energy-efficient routing schemes for underwater acoustic networks," *IEEE J. Sel. Areas Commun.*, vol. 26, no. 9, pp. 1754–1766, Dec. 2008.
[14] Y. Wei and D. S. Kim, "Exploiting cooperative relay for reliable communications in underwater acoustic sensor networks," in *Proc. IEEE MILCOM*, Oct. 2014, pp. 518–524.
[15] M. Stojanovic, "On the relationship between capacity and distance in an underwater acoustic communication channel," in *Proc. ACM WUWNet*, Sept. 2006, pp. 41–47.
[16] R. J. Urick, *Principles of underwater sound for engineers*. Tata McGraw-Hill Education, 1967.
[17] L. M. Brekhovskikh, Yu, L. M. Brekhovskikh, and Y. Lysanov, *Fundamentals of Ocean Acoustics*, 3rd ed. Springer, Mar. 2003.
[18] R. V. Hartley, "Transmission of information," *Bell Labs Technical Journal*, vol. 7, no. 3, pp. 535–563, 1928.
[19] C. E. Shannon, "A mathematical theory of communication," *ACM SIGMOBILE Mobile Computing and Communications Review*, vol. 5, no. 1, pp. 3–55, 2001.
[20] C. E. Shannon, "Communication in the presence of noise," *Proc. IRE*, vol. 37, no. 1, pp. 10–21, 1949.
[21] T.-L. Pham and D.-S. Kim, "Efficient forwarding protocol for dual-hop relaying wireless networks," *Wireless Personal Commun.*, vol. 89, no. 1, pp. 165–180, July 2016.
[22] S. Sahana, K. Singh, S. Das, and R. Kumar, "Energy efficient shortest path routing protocol in underwater sensor networks," in *Proc. ICCCA*, Apr. 2016, pp. 546–550.
[23] L. Freitag *et al*. "The whoi micro-modem: An acoustic communications and navigation system for multiple platforms," in *Proc. OCEANS*, Sept. 2005, pp. 1086–1092.
[24] 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 Trans. Wireless Commun.*, vol. 7, no. 8, pp. 3066–3078, Aug. 2008.

Hoa Tran-Dang received the B.E. degree in Electrical and Electronics Engineering from Hanoi University of Science and Technology (HUST), Vietnam and the M.S. degree in Electronics Engineering from Kumoh National Institute of Technology (KIT), South of Korea in 2010 and 2012, respectively. He pursued the Ph.D. degree with University of Lorraine, France during 2013-2017. He currently works in NSL Laboratory, Department of ICT Convergence Engineering at Kumoh National Institute of Technology, South of Korea as a Research Professor. His research interests include wireless sensor networks, Internet of things (IoT), physical internet, and radio resource management in wireless industrial networks.

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 at the Wireless Network Laboratory in the School of Electrical and Computer Engineering at Cornell University, NY. From 2007 to 2009, he was a Vistiting Professor with Department of Computer Science, University of California, Davis, CA. He is currently a Director of kit Convergence Research Institute and ICT Convergence Research Center (ITRC program) supported by Korean government at Kumoh National Institute of Technology. He is IEEE and ACM senior member. His current main research interests are real-time IoT, industrial wireless control network, networked embedded system and Fieldbus.