Towards Delay-Sensitive Routing in Underwater Wireless Sensor Networks

Mohsin Raza Jafri*a, Muhammad Moid Sandhu*a, Kamran Latifb,c, Zahoor Ali Khan*d, Ansar Ul Haque Yasare, Nadeem Javaida,f,*

*aEE dept, COMSATS Institute of Information Technology, Islamabad, Pakistan
*bCS dept, COMSATS Institute of Information Technology, Islamabad, Pakistan
*cNational Institute of Electronics (NIE), Islamabad, Pakistan
*dInternetworking Program, FE, Dalhousie University, Halifax, Canada
*eTransportation Research Institute (IMOB), Hasselt University, Diepenbeek, Belgium
*fCAST, COMSATS Institute of Information Technology, Islamabad, Pakistan

Abstract

In Underwater Acoustic Sensor Networks (UASNs), fundamental difference between operational methodologies of routing schemes arises due to the requirement of time-critical applications therefore, there is a need for the design of delay-sensitive techniques. In this paper, Delay-Sensitive Depth-Based Routing (DSDBR), Delay-Sensitive Energy Efficient Depth-Based Routing (DSEEDBR) and Delay-Sensitive Adaptive Mobility of Courier nodes in Threshold-optimized Depth-based routing (DSAMCTD) protocols are proposed to empower the depth-based routing schemes. The proposed approaches formulate delay-efficient Priority Factors (PF) and Delay-Sensitive Holding time (DS_H_T) to minimize end-to-end delay with a small decrease in network throughput. These schemes also employ an optimal weight function W_f for the computation of transmission loss and speed of received signal. Furthermore, solution for delay lies in efficient data forwarding, minimal relative transmissions in low-depth region and better forwarder selection. Simulations are performed to assess the proposed protocols and the results indicate that the three schemes largely minimize end-to-end delay of network.

Keywords: Underwater Acoustic Sensor Networks; Depth Based Routing; Weight Function; Priority Function

1. Introduction

From the very beginning, oceans are essential way of transportation, military actions and distributed tactical surveillance. For all these applications, Underwater Acoustic Sensor Networks (UASNs) employ sensor nodes to detect physical attributes such as temperature, pressure etc. There are vast applications of UASNs such as assisted navigation, ocean sampling, mine reconnaissance and pollution monitoring, which demand time-critical routing protocols.
These applications surpass the requirements of energy-efficient and delay-tolerant routing designs. Ian Akyildiz et. al 1 investigate several aspects of underwater routing and its challenges and categorize their issues according to network protocol stack. They also discuss open research issues in 2-dimensional and 3-dimensional UASNs. Depth-Based Routing (DBR) 2 proposes flooding based approach in which sensor nodes forward data solely on the basis of their depth information. It is one of the best localization-free routing schemes of UASN which utilizes acoustic signals to tackle error-prone underwater conditions. EEDBR 3 enhances the network lifetime and improves path loss by computing holding time on the bases of residual energy of sensor nodes. AMCTD 4 encourages the deployment of courier nodes and devises efficient weight functions WF to increase the stability period of the network. It also provides a paradigm to minimize noise and other attenuation losses for sensor nodes positioned in a low-depth region of UASN. In this paper, we have proposed improved delay-sensitive versions of DBR, EEDBR and AMCTD to make them adaptable for time-critical applications. We have applied delay and channel loss models in depth-based routing protocols of DBR, EEDBR and AMCTD to examine their effects in delay-sensitive routing. The main concern is to minimize huge propagation delays along with maintaining other parameters such as network lifetime and number of transmissions. We discuss the related work in section 2. Section 3 presents the problem statement of DBR, EEDBR and AMCTD. Sections 4, 5 and 6 contain brief explanation of our proposed protocols DSDBR, DSEEDBR and DSAMCTD respectively. Simulation results are presented in section 7 and finally, section 8 concludes the paper.

2. Related work

Extensive research has been done on UASN routing protocols in recent years due to their worth applications. Their primary requirement is adaptability with the delay-tolerant and delay-sensitive applications. Furthermore, the drawback of any specific method is viewed as an advantage to its contrasting scheme. Abdul Wahid et. al 5 investigate UASN routing schemes and classifies them according to their priorities in UASN. Sherif et. al 6 propose Delay Tolerant network (DTN) routing protocol to tackle continuous node movements and utilize the single-hop and multi-hop routing. Hanjiang Luo et. al 7 propose energy balancing strategies in an underwater moored monitoring system in order to deal with sparse conditions. They provide a mathematical model to investigate the power consumption of sensor nodes. In addition to the above mentioned schemes, there are also some delay-sensitive protocols proposed for UWSN. Mobicast Routing Protocol (MRP) 8 suggests adaptive mobility of Autonomous Underwater Vehicle (AUV) to collect data with a minimum end-to-end delay. Stefano et. al 9 try to minimize the packet latency and energy consumption of the nodes by optimized packet size selection along with examining its effects on MAC layer protocols. Dario Pompili et. al 10 suggest the paradigms for both delay-sensitive and delay-insensitive techniques in UWSN by formulating Integer Linear Programming models. Zhong et. al 11 suggest Multi-path Power control Transmission (MPT) protocol to ensure a guaranteed end-to-end delay and minimum Bit Error Rate (BER) in challenging acoustic channels. In 12, the authors devise multi-subpath routing to minimize propagation delays along with improving packet delivery ratio in UWSN.

3. Motivation

There is high end-to-end delay in DBR, EEDBR and AMCTD which is unsuitable for delay-sensitive routing applications. Following major observations were noticed in the above mentioned protocols:

- In DBR, there are distant transmissions between the sensor nodes specifically in the medium-depth region introducing large propagation delay.
- In EEDBR, the delay conditions are improved than in DBR however, there is lack of load balancing in the low-depth region due to multiple forwarding and relative transmissions of data packets.
- Presence of courier nodes improves the throughput in AMCTD, however it does not noticeably minimize end-to-end delay of network.
4. Delay-Sensitive DBR

DSDBR is an improved version of DBR, which not only performs routing on the basis of depth information but also employs Holding Time (HT) and depth threshold (dth). Each sensor node transmits the sensed data within its transmission range as shown in fig. 1. The neighbor node, at a depth lower than the source node and is located outside its dth limit, computes HT for received data packet. Depth threshold limit is given as:

\[ d_{th} < d_p - d_c \]  

(1)

d_c and d_p denote the depths of the current and previous node respectively during transfer of a packet.

4.1. Data Forwarding Phase

DSDBR works on the principle of greedy algorithm and nodes with a lower depth forward data towards BS. Each eligible neighbor computes Forwarding value \( F_i \) for the received packet as follows:

\[ F_i = \left( \frac{TL_i q_i}{\eta} \right) \]  

(2)

where, \( q_i \) is the speed of the received data packet in m/s and \( TL_i \) is the transmission loss of received data packets in dB. \( \eta \) is a scaling factor for \( F_i \). \( F_i \) depends upon Transmission Loss (TL) and speed of received data packet which is used to find intermediate forwarder in transmission range. \( F_i \) is used to compute \( W_F \) for received packet, which is expressed as:

\[ W_F = \alpha - F_i \]  

(3)

where, \( \alpha \) is used as a constant and depends upon the network size. The value of \( \alpha \) determines the difference between the \( F_i \) values of neighbors of the source node, which is further applied to calculate \( H_T \). Nodes having high \( F_i \) will have low \( W_F \) as well as \( H_T \), which is computed as:

\[ H_T = \left( \frac{W_F H_{max}}{\gamma A TL_{min}} \right) \]  

(4)
Using the equation (4), each node calculates $H_T$ for received packet during which, it keeps data packet in buffer. $TL_{\text{min}}$ is the minimum transmission loss between any two nodes in $dB$ and $v_{AC}$ is the speed of acoustic signal in $m/s$. $H_{\text{max}}$ is the maximum value of $H_t$ for any received packet. An optimal value of $H_T$ is used to minimize multiple transmissions of same packets, as nodes overhearing the received packets from low-depth nodes will not transmit the received data packets. Therefore, DSDBR aims to minimize end-to-end delay by improving $H_T$ computations criteria and $WF$ formulation. However, there is a trade-off between end-to-end delay and throughput in the stability period.

5. Delay-Sensitive Energy-Efficient DBR

DSSEEDBR provides enhanced network lifetime along with delay sensitivity to EEDBR by implementing adaptive variations in $d_{ih}$ for sensor nodes and Delay-Sensitive Holding time ($DS_H_T$). $DS_H_T$ is the heart of depth-based routing model and removes the inadequacy of multiple relative transmissions in EEDBR. Every receiving node before forwarding the data packet, computes the transmission loss and noise loss of the channel and depth difference in order to predict the time-lag of the packet to be forwarded.

5.1. Variations in $d_{ih}$

DSSEEDBR exploits the inefficient approach of a constant $d_{ih}$ in the entire network which causes more delay in the low-depth region. Transmissions by sensor nodes in the low-depth region cause high propagation delays. These transmissions may reduce the load on medium-depth region nodes on the cost of high noise loss in the upper region. We compute these losses along with considering the residual energy of medium-depth nodes and apply variable $d_{ih}$ for nodes according to their depth information. The sensor nodes deployed in low-depth and medium-depth regions have smaller $d_{ih}$ values than the high-depth nodes therefore, they will have increased number of neighbors avoiding distant transmissions.

5.2. $DS_H_T$ estimation

Our scheme proposes faster data forwarding mechanism than EEDBR by estimating $DS_H_T$ for forwarding data packets. After receiving these packets, eligible forwarders consider attenuation loss in computing $DS_H_T$. Since, our scheme is energy efficient as it utilizes residual energy of the forwarder node, hence $DS_H_T$ is computed as:

$$DS_H_T = \frac{A_L D_d R_i}{L_N v_{AC} E_{ini}}$$

(5)

where $A_L$ is the attenuation loss of received packet in $dB$, $D_d$ is the depth difference between sender and receiver node in meters and $R_i$ is the residual energy of a receiver node in joules. $L_N$ is the combined noise loss due to shipping, wind, turbulence and thermal activities in $dB$. $v_{AC}$ denotes speed of acoustic signal and $E_{ini}$ shows the initial energy of nodes. Node having low $A_L$ and $D_d$ will have lesser $DS_H_T$ than the other neighbours and will be selected as suitable forwarder.

6. Delay Sensitive AMCTD

Courier nodes help to minimize delay factor up to a large extent, when the sensor nodes adapt data forwarding priority according to the availability of courier nodes in their region. DSAMCTD employs variations in depth threshold with the changing depth of sensor nodes. Nodes apply different PF formulae for data forwarding with the help of which they compute their $H_T$ with varying network density. This parameter is based on the availability of neighbor nodes, depth information and residual energy of receiving node.
6.1. System Model and Network Initialization

AMCTD formulates energy-efficient $W_F$ to forward data along with availability of courier nodes. We have utilized $d_{th}$ variations according to depth information of sensor nodes. Nodes with higher depth have more $d_{th}$ than the other nodes. This minimizes distant transmissions in low-depth region.

6.2. PF Formulation

DSAMCTD devises $PFs$ for sensor nodes to manage delay-efficient data transmission. During initialization phase, each sensor estimates the number of neighbors within its transmission range and finds its $H_T$ on the basis of PF formulae. There are three different PF formulae designed to enhance availability of neighbors for selection of optimal data forwarders. Fig. ?? shows the mechanism of data transmission in DSAMCTD. Nodes having high $PF$ value will have shorter $H_T$ than the other nodes. Furthermore, nodes forward data using $PF_H$ in high network density, $PF_M$ in medium density and $PF_L$ in last rounds of network; when the network density gets sufficiently low.

$$PF_H = \left( \frac{H_T \max N_i R_i D_{\max}}{D_i E_{ini}} \right)$$

(6)

In the above equation, $N_i$ denotes number of neighbors of node $i$, $D_i$ is the depth of node $i$ in meters and $D_{max}$ is the maximum depth of network in meters. $PF_H$ encourages high availability of neighbors and residual energy instead of depth information in forwarder selection.

$$PF_M = \left( \frac{H_T \max (D_{max} - D_i) N_i E_{ini}}{D_i D_{max}} \right)$$

(7)

During instability period, $PF_M$ manages data forwarding by considering depth as a decision factor in the network.
In extreme sparse situation, \( PFL \) monitors the network by selecting nodes with high residual energy as optimal forwarder. If the number of dead nodes is less than \( \alpha_1 \), then the sensor nodes compute their \( H_T \) for the received data packets using \( PFL \). They utilize \( PF_M \) between \( \alpha_1 \) and \( \alpha_2 \) for forwarder selection, and in sparse conditions, \( PFL \) provides better performance when number of dead nodes is greater than \( \alpha_2 \). In this scenario, \( \alpha_1 \) and \( \alpha_2 \) are the limits for number of dead nodes.

\[
PFL = \left( \frac{H_{T_{\text{max}}} R_D}{D_{\text{max}} E_{\text{init}}} \right)
\]  

(8)

7. Performance Evaluation and Analysis

We examine the performance of DSDBR, DSEEDBR and DSAMCTD and analyze their simulated effects in realistic acoustic conditions. In all simulations, we have assumed a network dimension of 500x500x500m with multiple sinks deployed on the surface of water, with a random deployment of 225 sensor nodes. Each sensor node has a transmission range of 100 meters. Following the convention of existing depth-based routing schemes, we used acoustic modem of LinkQuest UWM1000 having a bit rate of 10kbps. According to the specifications of modem, the power consumption in transmitting, receiving, and idle mode are 2W, 0.1W, and 10mW respectively. The size of data packet is 50 bytes, while that of control packet is 8 bytes.

7.1. Comparison of DBR and DSDBR

First of all, we compare DBR and DSDBR to analyze the functioning of our proposed scheme in terms of different performance parameters. DSDBR faces tradeoff between end-to-end delay and network throughput. In the earlier rounds of DBR, there is an increase in number of transmissions which increases the network throughput along with end-to-end delay. Fig.3a depicts that in DBR, number of packets received by sink are higher than DSDBR. In the initial rounds, throughput of DSDBR is lower than DBR due to low stability period. It reduces the number of available forwarding nodes for remaining alive nodes. Fig.3b illustrates the decrement in delay of our proposed scheme in comparison to DBR. After 5000 rounds, there is a major decrease in delay of DSDBR at the cost of small decrement in network density. However, in DBR, there is increase in end-to-end delay which is primarily due to high TLs for remaining distant nodes. During the instability period of DSDBR, throughput remains higher than that of DBR along with minimum energy consumption and lesser end-to-end delay as shown in figs.3a and 3b. The key cause of reduced delay in DSDBR in later rounds is low network density and availability of suitable data forwarders.

Fig. 3: (a) Network throughput in DBR and DSDBR; (b) End-to-End delay in DBR and DSDBR.
Fig. 4: (a) Comparison of TL (dB) in EEDBR and DSEEDBR; (b) End-to-End delay in EEDBR and DSEEDBR.

7.2. Comparison of EEDBR and DSEEDBR

In fig. 4a, we compare TL of EEDBR and DSEEDBR. It illustrates that transmission loss is higher in EEDBR than the proposed scheme, which is caused by a large number of transmissions and multiple retransmissions for same packets. In EEDBR, due to high network density in initial rounds, there is lesser transmission loss which increases dramatically with a decrease in the number of available forwarders in low-depth regions. DSEEDBR maintains low TL throughout the network lifetime by decreasing load on low-depth nodes. Fig. 4b depicts average end-to-end delay in EEDBR and DSEEDBR. It shows gradual decrease in delay of DSEEDBR along with changes in TL of the network. It illustrates slower network activity in EEDBR which is not suitable for time-critical applications. After 2000 rounds, there is a sharp increase in delay of EEDBR due to quick energy consumption of nodes deployed in medium-depth region. DSEEDBR decreases end-to-end delay of the network by incrementing $d_n$ in high-depth area for forwarder selection considering low attenuation and noise losses in this region. Our proposed protocol compromises on network throughput to achieve low propagation delay.

7.3. Comparison of AMCTD and DSAMCTD

Fig. 5a shows the comparison of end-to-end delay between AMCTD and DSAMCTD. The delay in AMCTD is already less than that of DBR and EEDBR due to the involvement of courier nodes, however, there is a higher variation in end-to-end delay of AMCTD which is removed in our proposed scheme by introducing $W_f$. Sensor nodes having high number of neighbors have a greater $W_f$ than the other nodes and they are selected as optimal data forwarders. This reduces distant transmissions towards BS and utilizes the courier nodes in the high depth region of the network. DSAMCTD also maintains reasonable stability period by avoiding distant transmissions in the medium-depth region.
Fig. 5a and 5b clearly show the trade-off between the throughput and end-to-end delay of DSAMCTD. Moreover, AMCTD has much higher throughput in the stability period however, high variation in energy consumption of sensor nodes. We employed the mobility of courier nodes to achieve minimal delay without increasing network throughput. However, higher network throughput is maintained in the later rounds.

8. Conclusion

In this paper, we proposed delay-sensitive protocols as an improvement to localization-free routing schemes of DBR, EEDBR and AMCTD. In DSDBR, we used $F_s$ and $W_F s$ to devise better forwarder selection. In DSEEDBR, we introduced $d_h$ variation and provided an analysis to estimate $DS H_T$. It is found that distant transmissions in the low-depth region are the major causes of high propagation delays. In the improved version of AMCTD, we devise $PF s$ formulae for sensor nodes with varying network density and selecting a sensor node with higher neighbors as an optimal forwarder for data packets.

References