Underwater Acoustic Sensor Networks (UASNs) offer their practicable applications in seismic monitoring, sea mine detection, and disaster prevention. In these networks, 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 performance of the proposed schemes is validated in UASNs. All of the three schemes formulate delay-efficient Priority Factors (PF) and Delay-Sensitive Holding time ($T_{HS}$) 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 along with improving the transmission loss of network.

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 and pressure. There are vast applications of UASNs such as assisted navigation, ocean sampling, mine reconnaissance, and pollution monitoring, which demand time-critical and delay-sensitive routing protocols. These applications surpass the requirements of energy-efficient and delay-tolerant routing designs. Therefore, there is a need of delay-sensitive routing protocols in UASNs, which forward the sensed data towards the Base Station (BS) with a minimal time lag. There is also a requirement of routing protocols in large-scale distributed networks to tackle the high propagation delays in localization-free environment as the underwater activities encompass hundreds to thousands of kilometers. There are two major categories of underwater routing protocols: (i) localization-free and (ii) localization-based routing protocols. Localization-free routing protocols do not require location information of
sensor nodes for data forwarding; however, localization-based protocols route data towards the BS on the basis of location information of the sensor nodes.

In localization-free protocols, sensor nodes conventionally depend on their depth information to forward data efficiently, as it considers continuous movement of sensor nodes in aqueous environment. 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.

In this paper, we have proposed improved delay-sensitive versions of DBR, EEDBR, and AMCTD to make them adaptable for time-critical applications. This work is an extension of [2]. These new schemes are verified and validated through simulations in the UASNs. 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 prefer localization-free routing protocols as sensor nodes move with a speed of 2-3 knots and it is difficult to identify their location information. It is important to examine the deficiencies of these flooding-based protocols as they depict the practical acoustic conditions.

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.

Depth-Based Routing (DBR) [3] 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 [4] enhances the network lifetime and improves path loss by computing holding time ($H_f$) on the bases of residual energy of sensor nodes. AMCTD [5] encourages the deployment of courier nodes and devises efficient weight functions ($W_f$) 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.

Wahid and Dongkyun [6] investigate UASN routing schemes and classify them according to their priorities in UASN. Tolba et al. [7] propose Delay Tolerant network (DTN) routing protocol to tackle continuous node movements and utilize the single-hop and multihop routing. They also attempt to minimize collision overhead at the Medium Access Control (MAC) layer.

Luo et al. [8] 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. These schemes provide higher stability period at the cost of higher delay or increased path loss. Furthermore, there are also some energy-efficient protocols in all types of UWSNs such as Round-Based clustering (RBC) [9] and Link-State Based routing (LSB) [10]. The main designing concern of these schemes is the minimization of energy consumption of the sensor nodes. These protocols propose different technical solutions for this purpose at physical, MAC, and routing layer. These schemes assume the water condition, according to the depth of the sender and receiver node, as there is a large difference between the parameters of shallow and deep water. At the MAC layer, the major problem is the large number of transmission collisions which can also be handled by the routing protocols. Chao and Lu [11] minimize the transmission collisions by proposing an efficient multichannel MAC layer protocol. Moreover, RBC minimizes the amount of redundant data transmission by utilizing cluster formation. In [12], the authors study the effects of frequency scaling over channel capacity. They achieve a high quality of signal by utilizing multihop communication in dense UASNs.

In addition, to the above mentioned schemes, there are also some delay-sensitive protocols proposed for UWSN. Mobcast Routing Protocol (MRP) [13] suggests adaptive mobility of Autonomous Underwater Vehicle (AUV) to collect data with a minimum end-to-end delay. It applies “Appleslice” technique to solve the coverage hole problem with varying node density. Basagni et al. [14] minimize the packet latency and energy consumption of the sensor nodes by optimized packet size selection along with examining its effects on MAC layer protocols.

Pompili and Melodia [15] suggest the paradigms for both delay-sensitive and delay-insensitive techniques in UWSN by formulating Integer Linear Programming models. Zhou et al. [16] suggest Multipath Power control Transmission (MPT) protocol to ensure a guaranteed end-to-end delay and minimum Bit Error Rate (BER) in challenging acoustic channels. It formulates optimal energy distribution models for unipath and multipath communication. In [17], the authors devise multisubpath routing to minimize propagation delays along with improving packet delivery ratio in UWSN.

We have selected DBR, EEDBR, and AMCTD for the analysis because these are depth-based routing protocols. In this paper, the main focus is on the improvement of notable depth-based routing protocols in UWSNs. There is a large end-to-end delay in these protocols due to calculation of holding time and long transmission distance between sender and receiver node. Having minimized delay, these protocols perform well in the delay-sensitive applications of UWSNs. Moreover, EEDBR and AMCTD have high network throughput, whereas the major deficiency is high end-to-end delay which has been overcome by their delay-sensitive versions. DBR is the initial routing protocol in the category of depth-based routing and its major deficiency is also a high delay due to large nodal delay.

We discuss the underwater channel model in Section 3. Section 4 presents the problem statement of DBR, EEDBR, and AMCTD. Sections 5, 6, and 7 contain brief explanation of our proposed protocols DSDBR, DSEEDBR, and
In this section, we analyze the effects of acoustic channel characteristics on the speed and end-to-end delay of the signal. We propose an analytical model to compute the propagation delay in data transmissions, as shown in Figure 1. The propagation delay for acoustic signal is five times greater than the terrestrial radio signals due to multipath and fading effects and depends on the attenuation coefficient due to high BER in aqueous environment. The end-to-end delay between the sender and receiver is given by

\[
T_{E-E} = (n + 1) (T_{tx}) + n (T_{rx}) + T_p^d,
\]

where \(T_{tx}\) and \(T_{rx}\) are the transmission and receiving time consumed by a sensor node for a packet in seconds. \(n\) is the number of hops for a specific packet and \(T_{E-E}\) is the end-to-end delay whereas \(T_p^d\) is the overall propagation delay of packets between the source and BS expressed as

\[
T_{p}^d = T_{si}^{ab} + \sum_{i,j \in n} T_{ij}^{ab} + T_{j, b}^{ab} \quad n \geq 2 \land i, j \in n, \quad (2)
\]

\[
T_{p}^d = T_{si}^{ab} + T_{j, b}^{ab} \quad n = 1 \land i \in n, \quad (3)
\]

\[
T_{p}^d = T_{sb}^{ab} \quad n = 0. \quad (4)
\]

Equations (2), (3), and (4) show the computations of propagation delay for multihop, single-hop, and direct communication, respectively.

In (5), we compute the propagation delay \(T_p\) between any two nodes of the network. Propagation delay is the time consumed by the signal to cover the distance between sender and receiver. We assume \(d\) as the Euclidean distance between the two nodes and \(q\) as the speed of received acoustic signal which depends upon different parameters such as depth difference between sender and receiver. Propagation delay between two nodes calculated in [15] is given as

\[
T_p = \frac{d}{q}, \quad (5)
\]

where \(d\) is the distance between the sender and receiver in \(m\) and \(q\) is the speed of signal in m/s which is calculated as follows [18]:

\[
q = 1449.05 + 45.7t - 5.21t^2 + 0.23t^3
\]

\[
+ (1.333 - 0.126t + 0.009t^2)(S - 35)
\]

\[
+ 16.3z + 0.18z^2,
\]

\[
t = \frac{T}{10}.
\]

In the above equations, \(T\) is the temperature in °C, \(S\) is salinity in \(ppt\), and \(z\) is the depth in km. Above discussed equations compute the overall delay of packets between the source nodes and BS, by considering signal speed with the depth of water.

3.1. Acoustic Attenuation Models. Underwater channel efficiency depends primarily on the attenuation coefficient for the inter-nodal distances. This coefficient is characterized by different factors such as depth of sensor nodes and distances between them. Furthermore, path loss increases with the increase in frequency of signal. We have thoroughly reviewed the attenuation losses in both Thorps [19] and Monterey-Miami Parabolic Equation (MMPE) [20] models. Thorps computes the total attenuation loss \(A(l, f)\) by the summation of absorption effects and the spreading loss, which can be expressed as

\[
10 \log A (l, f) = k10 \log (l) + 110 \log \left(\alpha (f)\right). \quad (7)
\]

In (7), the first term refers to spreading loss and the second term denotes the absorption loss, which are measured in \(dBrePa\). The spreading coefficient \(k\) describes the geometry of the signal propagation (i.e., \(k = 1\) is cylindrical, \(k = 2\) is spherical, and \(k = 1.5\) is particle spreading [21]) and \(\alpha(f)\) is bandwidth efficiency measured in \(dB/Km\). \(l\) is the distance between the sender and receiver in \(km\) and \(f\) is the frequency of signal in \(kHz\).

Research shows that the molecular movement of acoustic signal is highly affected by the random noise and wave motion, which can be detected by increasing the complexity of the improved models along with their enhanced accuracy. MMPE [22] model computes the Transmission Loss (TL) as

\[
TL = m (f, s, d_A, d_B) + w(t) + e (n), \quad (8)
\]

where \(m(f, s, d_A, d_B)\) is the propagation loss due to haphazard and periodic constituents, incurred from the regression of MMPE data. \(f\) is the frequency of acoustic signal in kHz, \(d_A\) is the depth of sender node \(A\) in \(m\). \(d_B\) is the depth of receiver node \(B\) in \(m\). \(s\) is the Euclidean distance between node \(A\) and node \(B\) in \(m\). \(w(t)\) is the periodic function to estimate signal loss due to wave movement. \(e(n)\) is the signal loss function caused by random noise error.

Figures 2 and 3 show the effect of TL on DBR and EEDBR as predicted by Thorps and MMPE models.
4. Problem Statement

Depth-based routing protocols use natural characteristics of acoustic communication as they do not require localization information and completely depend upon the depth information of sensor nodes. There is high end-to-end delay in DBR, EEDBR, and AMCTD which is unsuitable for delay-sensitive routing applications. Therefore, in terms of high end-to-end delay, the following major observations were noticed in the above mentioned protocols.

(i) In DBR, there are distant transmissions between the sensor nodes specifically in the medium-depth region introducing large propagation delay.

(ii) 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 number of transmissions of data packets.

(iii) Presence of courier nodes improves the throughput in AMCTD but, however, does not minimize end-to-end delay of network remarkably.

In this paper, we propose improved delay-sensitive versions of DBR, EEDBR, and AMCTD to remove above-discussed deficiencies.

5. Delay-Sensitive DBR

Delay Sensitive Depth-Based Routing (DSDBR) is an improved version of DBR, which not only performs routing on the basis of depth information but also employs Holding Time \((H_T)\) and depth threshold \((d_{\text{th}})\). Each sensor node transmits the sensed data within its transmission range as shown in Figure 4. The neighbor node, at a depth lower than the source node and located outside its \(d_{\text{th}}\) limit, computes \(H_T\) for received data packet. \(d_{\text{th}}\) limit is given as

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

\(d_c\) and \(d_p\) denote the depths of the current and previous node, respectively, during transfer of a packet. \(H_T\) depends upon the weight function \((W_F)\) of the received data packet as discussed in next subsection. Figure 4 shows the mechanism of transmission in DSDBR. It shows that as the source node \(A\) transmits the packet, all the nodes in its transmission range receive the packet. These nodes compare the depth of \(A\)
with their depth. The three neighbors in the figure having more depth than A discard the packet. Now, the other four neighbors check that whether their depth falls under the limit of depth threshold or not. In Figure 4, a single neighbor in depth threshold limit also discards the packet. The other three eligible neighbors compute the Forwarding value ($F_i$) and Weight function ($W_F$) of the received packet using the parameters of received signal such as Transmission loss. By using $W_F$, each eligible node computes the $H_T$ for the received packet. $H_T$ is the time duration to hold the packet in queue. We found out that one of the neighbors having a depth between the other two eligible neighbors has less $H_T$ than the other two nodes. It transmits the packet earlier than the other nodes. Other two nodes receive the packet during their $H_T$ and discard it due to overhearing process. The same process continues until the packet reaches the sink.

5.1. 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:

$$F_i = \left( \frac{(\text{TL})_i q_i}{\eta} \right),$$  
(10)

where $q_i$ is the speed of the received data packet in m/s and $(\text{TL})_i$ is the TL of the received data packet i in dB. $\eta$ is a scaling factor for $F_i$, which is assumed as 1000. $F_i$ depends upon TL and $q$ of received data packet which is used to find intermediate forwarder in transmission range. Furthermore, $F_i$ is used to compute $W_F$ for received packet, which is expressed as

$$W_F = \alpha - F_i,$$  
(11)

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

$$H_T = \left( \frac{W_F H_{T \text{max}}}{v_{AC} T_{\text{min}}} \right).$$  
(12)

Using (12), each node calculates $H_T$ for received packet during which it keeps data packet in buffer. $T_{\text{min}}$ is the minimum TL between any two nodes in dB and $v_{AC}$ [23] is the speed of acoustic signal in m/s. $H_{T \text{max}}$ 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 these packets. Thus, DSDBR aims to minimize end-to-end delay in DBR to make it adaptable to time-critical applications by improving $H_T$ computations criteria and $W_F$ formulation. However, there is a trade-off between end-to-end delay and throughput in the stability period. Figure 5 depicts the forwarding mechanism of DSDBR.

6. Delay-Sensitive Energy-Efficient DBR

Delay-Sensitive Energy-Efficient DBR (DSEEDBR) provides enhanced network lifetime along with delay sensitivity to EEDBR by implementing Delay-Sensitive Holding time (DSH$_T$) and adaptive variations in $d_{th}$ for sensor nodes. DSH$_T$ is heart of depth-based routing model as it removes the inadequacy of multiple retransmissions in EEDBR. Every receiving node, before forwarding the data packet, computes the TL and noise loss of the channel and depth difference in order to predict the time-lag of the packet to be forwarded. Figure 6 shows data transmission in DSEEDBR. Figure 6 shows the mechanism of transmission in DSEEDBR. It shows that all the nodes in the range of source node A receive the packet. The four neighbors having more depth than A discard the packet. Now, the other five neighbors compare their depth with the limit of depth threshold. A single neighbor falling in depth threshold limit discards the packet. The other three eligible neighbors compute the DSH$_T$ of the received packet using the parameters of received signal such as attenuation loss. We found out that one of the neighbors has less DSH$_T$ than the other three nodes. It transmits the packet earlier than the other nodes. The link between this node and source node A is termed active link. Other two nodes receive the packet during their DSH$_T$ and discard it due to overhearing process.

6.1. Variations in $d_{th}$. DSEEDBR exploits the inefficient approach of constant $d_{th}$ 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 losses in the upper region. We compute these losses along with considering the residual energy of medium-depth nodes and apply variable $d_{th}$ for nodes according to their depth information.
Algorithm 1: Variations in Depth threshold in EEDSDBR.

Therefore, they will have increased number of neighbors avoiding distant transmissions. Algorithm 1 shows adaptive variations in \( d_{th} \) for sensor nodes according to their depth information.

6.2. DSH\(_T\) Estimation. DSEEDBR proposes faster data forwarding mechanism than EEDBR by estimating DSH\(_T\) for forwarding data packets. After receiving these packets, eligible forwarders consider attenuation loss \( A_L \) [24] in computing DSH\(_T\). Since, our scheme is energy efficient (as it utilizes residual energy of the forwarder node), DSH is computed as

\[
DSH_T = \frac{A_L D_d R_i}{L_N V_A C E_{ini}},
\]

where \( A_L \) denotes attenuation loss of received data packet in dB, \( D_d \) is the depth difference between sender and receiver node in \( m \), and \( R_i \) is the residual energy of a receiver node in \( J \). \( L_N \) [25] is the combined noise loss due to shipping, wind, turbulence, and thermal activities in dB and \( E_{ini} \) shows the initial energy of nodes in \( J \). Nodes having low \( A_L \) and \( D_d \) will have lesser DSH\(_T\) than the other neighbours and will be selected as suitable forwarder.

7. Delay Sensitive AMCTD

Delay-Sensitive AMCTD (DSAMCTD) employs variations in \( d_{th} \) with the changing depth of sensor nodes. In this scheme, courier nodes largely minimize the delay factor as sensor nodes adapt their priority of data forwarding according to the presence of courier nodes. Nodes apply different Priority Factor (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 source node. Our scheme prioritizes distant transmissions with decreasing network density to facilitate the quick movement of courier nodes.

7.1. 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 increases distant transmissions in high-depth regions and, however, reduces them in low-depth region. Flow diagram (Figure 7) depicts the variation of \( d_{th} \) in DSAMCTD. In this
PF_{H} encourages high availability of neighbours and residual energy instead of depth information in forwarder selection. Consider

\[ \text{PF}_{H} = \left( \frac{H_{T_{\text{max}}} N_{i} R_{i} D_{\text{max}}}{D_{i} E_{\text{ini}}} \right). \tag{14} \]

During instability period, PF_{M} manages data forwarding by considering depth as a decision factor in the network. Consider

\[ \text{PF}_{M} = \left( \frac{H_{T_{\text{max}}} R_{i} D_{i}}{D_{\text{max}} E_{\text{ini}}} \right). \tag{15} \]

In extreme sparse situation, PF_{L} monitors the network by selecting nodes with high residual energy as optimal forwarder. Figure 9 shows that 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 PF_{H}. They utilize PF_{M} between \( \alpha_{1} \) and \( \alpha_{2} \) for forwarder selection, and, in sparse conditions, PF_{L} provides better performance for time-critical applications when the number of dead nodes is greater than \( \alpha_{2} \). Figure 8 shows the mechanism of transmission in DSAMCTD. It shows that the four neighbors having more depth than \( A \) discard the packet after receiving packet. Now, a single neighbor in depth threshold limit also discards the packet. The other three eligible neighbors check out the number of alive nodes and network density by using the received information from the sink. If the network density is high, the three eligible nodes compute the PF_{H} of the received packet using the parameters of received signal. By using PF_{H}, these nodes compute the \( H_{T} \) for the received packet. We found out that one of the neighbors has less \( H_{T} \) than the other two nodes. It transmits the packet earlier than the other nodes. Other two nodes receive the packet during their \( H_{T} \) and discard it due to overhearing process. If the network density is medium, the three eligible nodes compute the PF_{M} of the received packet. By using PF_{M}, these nodes compute \( H_{T} \) for the received packet. Neighbor having less \( H_{T} \) than the other two nodes transmits the packet earlier than the other nodes. If the network density is low, the three eligible nodes compute the PF_{L} of the received packet. By using PF_{L}, these nodes compute \( H_{T} \) for the received packet. Neighbor having less \( H_{T} \) than the other two nodes transmits the packet earlier than the other nodes. Therefore, there are three different data forwarders according to the network density.

8. Performance Evaluation and Analysis

In this section, we examine the performance of DSDBR, DSEEEDBR, and DSAMCTD and analyze their simulated effects in realistic acoustic conditions. All the three proposed schemes improve the end-to-end delay in the routing protocols of DBR, EEDBR, and AMCTD by allowing small decrease in network throughput. Using these performance parameters, we estimate the TL specifically in the low-depth region in order to provide efficient data forwarding. Effects of combined noise caused by shipping, turbulence, and thermal activity have been calculated. Same simulation scenario and specifications are employed for all the proposed protocols.
8.1. Simulation Scenario. In all simulations, we have assumed a network dimension of 500 m × 500 m × 500 m 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 an acoustic modem of LinkQuest UWM1000 [26] having a bit rate of 10 kbps. According to the specifications of modem, the power consumption in transmitting, receiving, and idle mode is 2 W, 0.1 W, and 10 mW, respectively. The size of data packet is 50 bytes, while that of control packet is 8 bytes. Moreover, we minimize collisions at MAC layer by implementing 802.11-DYNAV [27] protocol as a core MAC protocol. The initial energy of the sensor node is set as 20 joules.

8.2. Simulation Results and Analysis. This section is devoted for the performance evaluation, verification, validation, and comparison of our three proposed protocols with the conventional ones in Wireless Sensor Networks (particularly UASNs). In the following subsections, each enhanced scheme is compared with the existing one.

8.2.1. 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. The default transmission time and receiving time of data packet for all sensor nodes are 40 ms and those of control packets are 10 ms. We also assume that sensor nodes employ a frequency of 25 kHz for acoustic communication. In Figure 10, we analyze the total energy consumption in DBR and DSDBR. DSDBR faces tradeoff between decreased end-to-end delay (Figure 12) and increased total energy consumption; however, it allows a small decrease in network throughput (Figure 11). 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. In DSDBR, the network attempts to remove distant transmissions by selecting optimal data forwarders on the basis of their received packet’s TL and $q$. Figure 11 depicts that, in DBR, a number of packets received by sink are higher than DSDBR. In the initial rounds, throughput of DSDBR is lower than that of DBR. In DBR, high throughput in the initial rounds reduces the number of available forwarding nodes during instability period. In later rounds of DBR, there is a quick average energy consumption of sensor nodes causing creation of energy holes in the network.

Figure 12 illustrates the average 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. Furthermore, end-to-end delay depends upon salinity, temperature, depth, and TL of an acoustic signal. Nodal delay is also important; however, propagation delay mainly affects total end-to-end delay. After 1000 rounds, during the instability period of DSDBR, throughput remains higher than that of DBR along with minimum energy consumption and lesser end-to-end delay.
delay as shown in Figures 9, 10, and 11. The key cause of reduced delay in DSDBR in later rounds is low network density and availability of suitable data forwarders. Therefore, DSDBR is 48% more efficient than DBR in terms of end-to-end delay by compromising on low throughput and less stability period. Figure 13 shows that DBR has larger delay than DSDBR with the change in number of nodes. As the number of nodes increases, the delay in DBR is increased largely due to large aggregated holding time. In DSDBR, there is not a large increase in delay with increase in number of nodes due to selection of data forwards at the intermediate depth difference from the sender.

8.2.2. Comparison of EEDBR and DSEEDBR. In Figure 14, we compare TL of EEDBR and DSEEDBR. It illustrates that TL 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 less transmission loss which increases dramatically with a decrease in the number of available forwards in low-depth regions. Nevertheless, it delivers higher throughput than our proposed scheme due to increased stability period. DSEEDBR maintains low TL throughout the network lifetime by decreasing load on low-depth nodes; however, it compromises on network throughput in the initial rounds.

Figure 15 depicts average end-to-end delay in EEDBR and DSEEDBR. It shows gradual decrease in delay of DSEEDBR along with changes in TL (Figure 16) 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 $d_{th}$ in high-depth area for forwarder selection considering low attenuation and noise losses in this region.

Figure 16 shows the comparison of number of transmissions in EEDBR and DSEEDBR. It also shows that, in spite of low throughput in stability period before 2000 rounds, there are a high number of transmissions in EEDBR which increase rapidly in the later rounds.

Our proposed protocol minimizes delay by reducing the number of transmissions in the network. It compromises on network throughput to achieve low $T_p$. Global load balancing is achieved in DSEEDBR which results in an almost same number of transmissions throughout the entire lifetime. Simulations show that DSEEDBR is 68% more delay-efficient than EEDBR which is highly suitable for applications requiring high network lifetime and low network delay. Figure 17 shows that DSEEDBR has decreased end-to-end delay than EEDBR. It is due to the fact that speed of received signal defines the holding time. Neighbors having high depth difference but low Euclidean distance are selected as the data forwarder of the source node. It has less holding time than the other neighbors which causes decrease in delay. As the number of nodes is 225, there is a large improvement in delay condition in DSEEDBR due to efficient holding time computation.

8.2.3. Comparison of AMCTD and DSAMCTD. Figure 18 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 high variation in end-to-end delay of AMCTD which is removed in our proposed scheme by introducing $W_F$. Sensor nodes having higher 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.

Figure 19 illustrates total energy consumption in the schemes of AMCTD and DSAMCTD. There is a continuous variation in results of AMCTD due to movement of courier nodes. Our scheme maintains energy consumption in entire lifetime by adaptive $d_{th}$. It prioritizes depth information of sensor nodes to compute its $W_F$. 
Figures 18 and 20 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. According to our computations, DSAMCTD is 56% more efficient than AMCTD in terms of end-to-end delay in the network. Figure 21 shows the comparison of delay in AMCTD and DSAMCTD with the change in number of nodes in the network. It also shows the improved performance of DSAMCTD. It shows the equally efficient performance of priority factors in high, medium, and low network density.

9. Conclusion and Future Work

In this paper, we propose delay-sensitive protocols as an improvement to localization-free routing schemes of DBR, EEDBR, and AMCTD. We validate and verify the proposed schemes through extensive simulations in Wireless Sensor Networks (UASNs). In DSDBR, we use $F_i$ and $W_F$ to devise better forwarder selection. In DSEEDBR, we introduce $d_{th}$ variation and provide an analysis to estimate DSH$_T$. It is observed that distant transmissions in the low-depth region...
are the major causes of high propagation delays. Therefore, we eliminate large number of transmissions caused by turbulence and thermal activities. In the improved version of AMCTD, we devise PF formulae for sensor nodes with varying network density and selecting a sensor node with higher neighbors as an optimal forwarder for data packets. We succeed in guaranteeing minimal end-to-end delay by employing adaptive mobility of courier nodes allowing a slight decrease in network throughput.

In our future work, we aim to focus on the design of delay sensitive schemes for localization based routing protocols in order to achieve a realistic approach for time-critical applications of UWSNs.

**Notations**

- $N_i$: Number of neighbors of node $i$
- $R_i$: Residual energy of node $i$ in joules
- $D_i$: Depth of node $i$ in meters
- $E_{ini}$: Initial energy of any node in joules
- $H_{T,max}$: Maximum $H_T$ for any node in seconds
- $D_{max}$: Maximum depth of network in meters
- $PF_{Hi}$: Priority factor for sensor nodes in high network density (DSAMCTD)
- $PF_{Mi}$: Priority factor for sensor nodes in medium network density (DSAMCTD)
- $PF_{Li}$: Priority factor for sensor nodes in low network density (DSAMCTD)
- $\alpha$: A constant value assigned according to network size (DSAMCTD)
- $\alpha_1$: Lower limit for number of dead nodes (DSAMCTD)
- $\alpha_2$: Upper limit for number of dead nodes (DSAMCTD)

**Conflict of Interests**

The authors declare that there is no conflict of interests regarding the publication of this paper.

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