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Research Article

An Energy Efficient Localization-Free Routing Protocol for Underwater Wireless Sensor Networks

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Recently, underwater wireless sensor networks (UWSNs) have attracted much research attention from both academia and industry, in order to explore the vast underwater environment. UWSNs have peculiar characteristics; that is, they have large propagation delay, high error rate, low bandwidth, and limited energy. Therefore, designing network/routing protocols for UWSNs is very challenging. Also, in UWSNs, improving the energy efficiency is one of the most important issues since the replacement of the batteries of underwater sensor nodes is very expensive due to the unpleasant underwater environment. In this paper, we therefore propose an energy efficient routing protocol, named (energy-efficient depth-based routing protocol) EEDBR for UWSNs. EEDBR utilizes the depth of sensor nodes for forwarding data packets. Furthermore, the residual energy of sensor nodes is also taken into account in order to improve the network lifetime. Based on the comprehensive simulation using NS2, we observe that EEDBR contributes to the performance improvements in terms of the network lifetime, energy consumption, and end-to-end delay. A previous version of this paper was accepted in AST-2011 conference.

1. Introduction

The earth is a water planet, where more than 70% of its area spans over water. Only less than 10% of the water volumes (oceans) have been investigated, while a large area still remains unexplored. The exploration of oceans is getting more attention due to their usefulness such as presence of natural resources, defense, and means of Corresponding author: Dongkyun Kim transportation, and so forth. However, the traditional approaches for monitoring oceans have many limitations such as high cost, longer time of accessing the outcome of monitoring, and the unsuitable underwater environment for human presence, and so forth. Hence, underwater wireless sensor networks (UWSNs) are considered as important alternatives for exploring the oceans.

Recently, UWSNs have attracted much research attention from both academia and industry, in order to explore the vast underwater environment. UWSNs enable a large number of applications such as environmental monitoring for scientific exploration, disaster prevention, assisted navigation, and oil/gas spills monitoring, and so forth.

Terrestrial sensor networks (i.e., ground-based sensor networks) are well investigated, and many communication protocols have been proposed for such networks. However, UWSNs have different characteristics than the terrestrial sensor networks. The major difference is the employment of the acoustic signals in UWSNs, in contrast to terrestrial sensor network where the radio signals are used as a communication media. The transition from the radio to the acoustic signals is due to the poor performance of radio signals in water. The radio signals propagate large distances at extra low frequencies, requiring large antennas and high transmission power.

The employment of acoustic signals as the communication media imposes many distinctive challenges on UWSNs. In general, the UWSNs have the following intrinsic characteristics. The acoustic signals have long propagation delay (i.e., 1500 m/sec), that is, five orders of magnitude higher than the radio signals used in terrestrial sensor networks. The available bandwidth is limited due to attenuation and high absorption factor of acoustic signals. The link quality is severely affected by the multipath fading and refractive properties of sound channels. Therefore, the bit error rates are typically very high [1, 2].

Since the protocols proposed for terrestrial sensor networks are developed on the basis of the radio signals' characteristics such as low propagation delay and high bandwidth. Therefore, they cannot be directly applied to UWSNs. Thus, enormous efforts have been made for designing efficient communication protocols while taking into account the characteristics of the UWSNs.

The protocols proposed for UWSNs have addressed various issues concerning the characteristics of the UWSNs. Particularly, improving the network lifetime is an important issue in UWSNs since the replacement of the batteries of underwater nodes is very expensive due to harsh underwater environment. Therefore, the network protocol in UWSNs should be designed considering the energy efficiency to improve the network life-time. The underwater sensor nodes consume more energy in transmitting than receiving a packet. Therefore, in order to reduce energy consumption, consequently improving network life-time, the number of transmissions needs to be reduced. In addition, one of the important issues for improving the network lifetime is to balance the energy consumption among the sensor nodes. The workload should be equally divided among all the sensor nodes over a path from a source towards a destination.

In this paper, we therefore propose an energy-efficient depth-based routing protocol (named EEDBR) that performs energy balancing and reduces the number of transmissions of sensor nodes in order to improve the network life-time. In EEDBR, while forwarding a data packet from a sensor node to a sink, the packet is transmitted by some selected nodes. The selection of the nodes is based on the depth and residual energy. The process is as follows. Each sender broadcasts the data packet including a list of its neighbors' IDs, which contains only the IDs of the neighbors having smaller depths than the sender. Hence, only the selected neighboring nodes are allowed to forward the packet. Furthermore, EEDBR performs energy balancing by utilizing the residual energy information of sensor nodes. In EEDBR, sensor nodes hold the packet for a certain time before forwarding. The holding time is based on the residual energy of sensor nodes. A node having high residual energy has a short holding time compared to the nodes having low energy. Hence, the node with high residual energy forwards the packet, and the low energy nodes suppress their transmissions upon overhearing the transmission of the same packet. In this way, the energy balancing is achieved. Due to the energy balancing, the sensor nodes consume their energy parallelly, and none of the sensor node's battery is exhausted earlier than others. Hence, the overall network life-time is improved.

The rest of the paper is organized as follows. In Section 2, we review some related routing protocols and their problems. In Section 3, our proposed routing protocol, EEDBR, is described in detail. Section 4 presents the performance evaluation of EEDBR. Finally, conclusions are drawn in Section 5.

2. Related Work

In this section, we present some related routing protocols available in the literature. We take into account the well-known routing protocols proposed for UWSNs. We divide this section into two subsections: localization-based routing protocols and localization-free routing protocols.

2.1. Localization-Based Routing Protocols. In this section, some routing protocols which are based on the localization of the sensor nodes are presented. In [3], a vector based routing protocol called (vector based forwarding) VBF was proposed. The data forwarding in VBF is as follows. A source node, having a data packet to transmit, computes a vector from itself towards the destination/sink node. The source node then broadcasts the data packet including its position/location information in the data packet. In VBF, the nodes near the computed vector are used as relay nodes for forwarding the data packet. Among all the receiving nodes of a broadcast from a sender, only the nodes located in a predefined radius around the computed vector participate in the forwarding of the data packet. The employment of the predefined radius allows a reduced number of nodes to forward the data packet. Hence, the proposed scheme employs the concept of controlled flooding in the network. However, the limitation of the proposed scheme lies in requiring the localization of sensor nodes, which itself is a crucial issue in UWSNs. Furthermore, in case of sparse networks, the unavailability of sensor nodes in the predefined radius affects the performance.

In [4], a routing protocol called (hop by hop vector based forwarding) HHVBF was proposed. HHVBF is the successor of VBF, where the vector is computed on per hop basis. In HHVBF, due to the computation of the vector on per hop basis, performance improvements are achieved over VBF. However, HHVBF still requires the localization of sensor nodes, which limits the applicability of the proposed scheme in real environment.

In [5], a routing protocol called FBR (Focused Beam Routing) protocol was proposed. FBR is a cross-layer approach where different transmission power levels are used during the forwarding of the data packet. The sender of the data packet transmits an RTS packet with a certain transmission power level. If a CTS reply is received from a relay node residing closer to the sink node, the data packet is transmitted to that relay node. Otherwise, the transmission power level is increased to a higher level. FBR uses a range of transmission power levels for example, P_1 to P_N. The limitation of the FBR protocol lies in the assumption that the source node knows its own location and the location of the destination/sink node. Furthermore, the use of RTS/CTS during the forwarding of the data packets causes increased delay and excessive energy consumption. In [6], a routing protocol called (directional flooding-based routing) DFR was proposed. DFR is another routing protocol with the assumption of the localization of sensor nodes.

In [7], (sector based routing with destination location prediction) SBR-DLP was proposed. In SBR-DLP, it is assumed that a mobile sink is available in the network and

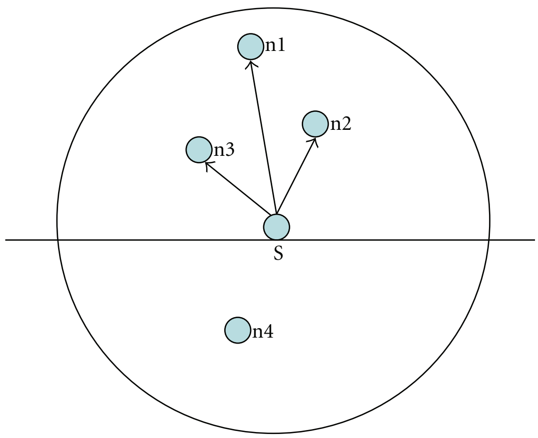


Figure 1: Scenario illustrating drawback of DBR.

that each sensor node is aware of the movement schedule of the mobile sink. The data forwarding process is as follows. A source node broadcasts a chk_ngb packet. The neighboring nodes reply with a chk_ngb_reply packet. The chk_ngb_reply packet contains the sector number of the neighboring nodes. The sectors are computed based on the distance from the vector (i.e., the vector between the source and the sink node). Upon receiving chk_ngb_reply packets from its neighbors, the source node assigns priorities to the neighboring nodes based on the sector number. Then, the neighboring node closest to the mobile sink is selected as a forwarder. The limitations of the proposed scheme are in requiring a localization technique, a large delay due to chk_ngb/chk_ngb_reply packets and the hard assumptions.

2.2. Localization-Free Routing Protocols. In this section, we present some localization-free routing protocols for UWSNs. In [8], a localization-free routing protocol called (depth based routing) DBR was proposed. DBR uses the depth of the sensor nodes as a metric for forwarding data packets. During data forwarding, the sender includes its depth in the data packet. The receiving nodes compare their depths to the depth of the sender. The node having smaller depth participates in forwarding the data packet. Each node has a certain holding time for each data packet, where the nodes having smaller depths have a short holding time compared to the nodes having higher depths. Since only the depth of sensor nodes is used as a metric for forwarding, most of the time, the nodes having smaller depths are involved in forwarding. Hence, such nodes die earlier than the other nodes in the network, which creates the routing holes in the network. Such a scenario is illustrated using Figure 1.

In Figure 1, node S is the sender of the packet, and nodes n1, n2, n3, and n4 are the receiving nodes. According to the approach employed by DBR, nodes n1, n2, and n3 are eligible for forwarding the packet because of having smaller depths than the sending node S. However, every time, the packet is forwarded by node n1 since node n1 has lower depth than the nodes n1 and n2, therefore, having short holding time. Consequently, due to the frequent forwarding, node n1 will die earlier than node n2 and node n3, which will create a routing hole in the network. Since all the nodes have the same approach of forwarding the data packets, routing holes are created all over the network. Due to the routing holes, the network is partitioned into parts which affect the network lifetime.

Furthermore, in DBR, with the increase in network density, the number of redundant transmissions also increases because the probability of small difference among nodes' depths also increases with the network density and the nodes having similar depths also have similar holding times. Due to the long propagation delay in underwater environment, before overhearing the same packet from a sender, a node's timer expires. Consequently, that node also transmits the packet. Hence, all the nodes which are having small differences among their holding times will transmit the packet before overhearing the same packet from other nodes. Thus, a lot of redundant packets will be transmitted, leading to excessive energy consumption.

In [9], H^2-DAB (hop-by-hop dynamic addressing based) routing protocol was proposed. H^2-DAB assigns a unique address (called HopID) to each sensor node based on the hop count from the sink node. The process is as follows. The sink node broadcasts a Hello packet. Each receiving node is assigned a HopID. Then, the receiving nodes increment the HopID and rebroadcast the Hello packet including the updated HopID. Since the HopID is increased hop by hop, the sensor nodes closer to the sink will be assigned smaller HopIDs than the nodes away from the sink. During the forwarding of data packets, the nodes having small HopIDs are selected for forwarding the data packets. Similar to DBR, the nodes having small HopIDs are frequently used for forwarding the data packets. Hence, these nodes having small HopIDs die earlier than the other nodes in the network. In addition, only hop count-based metric is not suitable in a resource-constrained network as UWSN. Furthermore, H^2-DAB uses *inquiry request* and *inquiry reply* packets during the forwarding of the data packets, which is expensive in terms of delay and energy.

In [10], Winston et al. proposed a virtual sink architecture where multiple sinks are assumed connected to each other. In the proposed scheme, each sink broadcasts a Hello packet (called hop count update packet). Upon receiving the Hello packet, each sensor node is assigned a hop count value. During the forwarding of the data packets from a source towards a sink node, these hop count values are used in the selection of a next forwarding node. The proposed scheme's limitations are the redundant transmissions (i.e., the transmission of the same packet towards multiple sinks) and the hard assumption of the connectivity among the sink nodes.

In [11], a network protocol called (multipath power-control transmission) MPT was proposed. MPT uses a cross layer approach, it combines power control with multi-path routing. The proposed scheme is divided into three phases: *multipath routing*, *source-initiated power-control transmission* and *destination node's packet combining*. Initially, the source node transmits a route request packet, the destination node reply with multiple route reply packets. Since the route request is broadcasted, therefore, the route request packet follows multiple paths towards the destination. Consequently, multiple route reply packets, following different paths, are received by the source node. Then an optimum number of paths are selected based on the path length and the number of paths. Source node also computes optimal energy distribution along a path based on the collected information (i.e., number of paths, number of hops in each path, perhop distance) during path establishment phase. The optimal energy distribution information is also included in the data packet, and based on this information each forwarder selects its transmission power. Finally, upon receiving the data packet, the destination node combines multiple erroneous copies (since some packets might be corrupted) of a packet received from multiple paths into a single copy to recover the original packet. The limitations of the proposed scheme are the redundant packets' transmissions and probabilistic approach used in the computation of optimal energy distribution.

In this paper, similar to DBR, we also employ the depth of sensor nodes for the selection of the forwarding nodes. However, our proposed scheme is different from DBR as follows.

(1) DBR uses only the depth of sensor nodes without taking into account the residual energy of the sensor nodes. In addition, in DBR, there is no method/approach for energy balancing among sensor nodes. In contrast, in our proposed scheme, the energy balancing of sensor nodes is employed in order to improve the network life-time.

(2) In DBR, the number of forwarding nodes increases as the network density increases. However, in our proposed scheme, the number of forwarding nodes is restricted on the basis of not only the depth but also the residual energy of the sensor nodes.

(3) DBR is a receiver-based approach, where the receiving nodes decide whether to forward the received data packet or not. There is a high probability of redundant transmissions in a receiver-based approach due to the lack of neighboring nodes' information such as depth and residual energy. In contrast, our scheme is a sender-based approach where the sender decides the forwarding nodes based on the neighboring nodes' depths and residual energy information. Hence, the sender can select a limited number of suitable forwarding nodes.

3. Our Proposed Protocol: Energy Efficient Depth-Based Routing Protocol (EEDBR)

In this section, we introduce our proposed routing protocol, EEDBR, in detail. EEDBR consists of two phases: knowledge acquisition phase and data forwarding phase. During the knowledge acquisition phase, sensor nodes share their depth and residual energy information among their neighbors. In the data forwarding phase, data packets are transmitted from the sensor nodes to the sink node.

We have divided this section into three subsections: network architecture, knowledge acquisition phase and data forwarding phase.

3.1. Network Architecture. Figure 2 shows the architecture of UWSN. Multiple sink nodes are deployed on the water surface, and the sensor nodes are deployed underwater from the top to the bottom of the deployment region. It is assumed that the sink nodes are equipped with the acoustic and radio modems. These sink nodes use acoustic modems, for communication with the underwater sensor nodes, and the radio modems, for communication with other sinks or an onshore data center. Since the radio communication is much faster than the acoustic communication, the data packet once received at any sink is considered delivered to all sinks and the onshore data center.

3.2. Knowledge Acquisition Phase. During this phase, the sensor nodes share their depth and residual energy information among their neighbors. The purpose of this sharing is to allow the sensor nodes to select the most suitable neighbors as forwarders during the data forwarding phase. When a sensor node has a data packet to send to the sink node, the depth and the residual energy information are used in the selection of forwarding nodes. In this knowledge acquisition phase, knowledge means the depth and residual energy of a sensor node.

The knowledge acquisition process is as follows. Each sensor node broadcasts a *Hello* packet to its one hop neighbors. The *Hello* packet contains the depth and the residual energy of the broadcasting node. The format of the *Hello* packet is shown in Figure 3. Upon receiving the *Hello* packet, the neighboring nodes store the depth and the residual energy information of those sensor nodes having smaller depth. The neighboring nodes only store the information about the sensor nodes having smaller depths since it is obvious that the data packets are transmitted towards the sink nodes residing on the water surface. Hence, storing the depth and residual energy information of all the neighboring nodes is not required, which lessens the burden of storing a large number of data.

It is reported that, in UWSNs, the sensor nodes reside at the same depth. This is because the sensor nodes move with water currents in horizontal direction, and the movements in vertical direction are almost negligible [4]. Hence, the updating of the depth information is not significant. However, the residual energy of the sensor nodes changes over time due to the different operations, that is, transmitting, receiving, processing, and idle listening. Therefore, the residual energy information of the sensor nodes needs to be updated. For this purpose, a distributed approach is employed in our proposed scheme. Each sensor node checks its residual energy on an interval basis. If the difference between the current and previous residual energy of a sensor node is larger than a threshold (i.e., a system parameter), that sensor node broadcasts the *Hello* packet including the updated residual energy to its one-hop neighbors. In this way, the residual energy information of the sensor nodes is updated among the

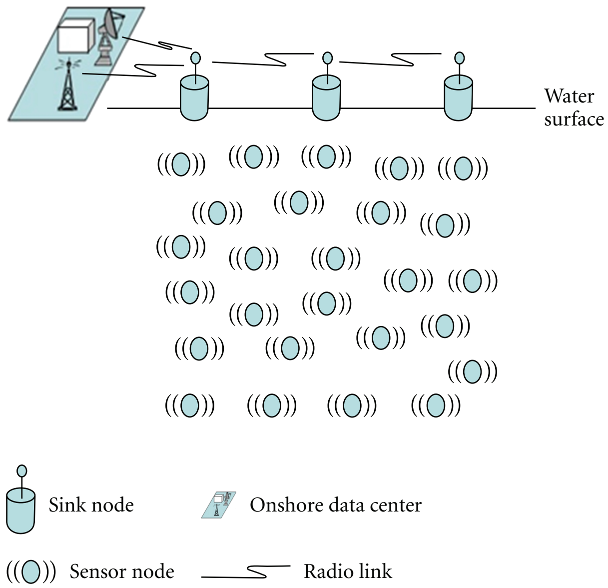


Figure 2: Architecture of an underwater wirless sensor network.

Sender ID	Residual energy	Depth

Figure 3: Format of the hello packet.

neighboring nodes. Furthermore, the knowledge acquisition phase is executed on an interval basis. This is done to update the sensor nodes about their most recent neighboring nodes and their updated residual energy and depths. However, the interval of knowledge acquisition phase is set long in order to avoid the overhead due to the broadcasts of the *Hello* packets. Hence, there is a tradeoff between the overhead and having the updated information about the neighboring nodes.

3.3. Data Forwarding Phase. During this phase, the data packets are forwarded from a source node towards a destination/sink node on the basis of the depth and the residual energy information of the sensor nodes. The information about the depth of the sensor nodes allows the selection of those forwarding nodes which are closer to the sink than the sender of the data packet. In addition, the residual energy information about the sensor nodes is used to select the node having high residual energy among its neighbors. The selection of the node having high energy attempts to balance the energy consumption among the sensor nodes. In EEDBR, since each sensor node has the information about its neighbors' depth and the residual energy, a sending node can select the most suitable next hop forwarding nodes. Therefore, the sending node selects a set of forwarding nodes among its neighbors having smaller depth than itself. The set of forwarding nodes is included as a list of IDs in the data packet.

Upon receiving the data packet, the forwarding nodes hold the packet for a certain time based on their residual energy. The sensor node having more residual energy has a short holding time. The holding time (T) is computed using (1).

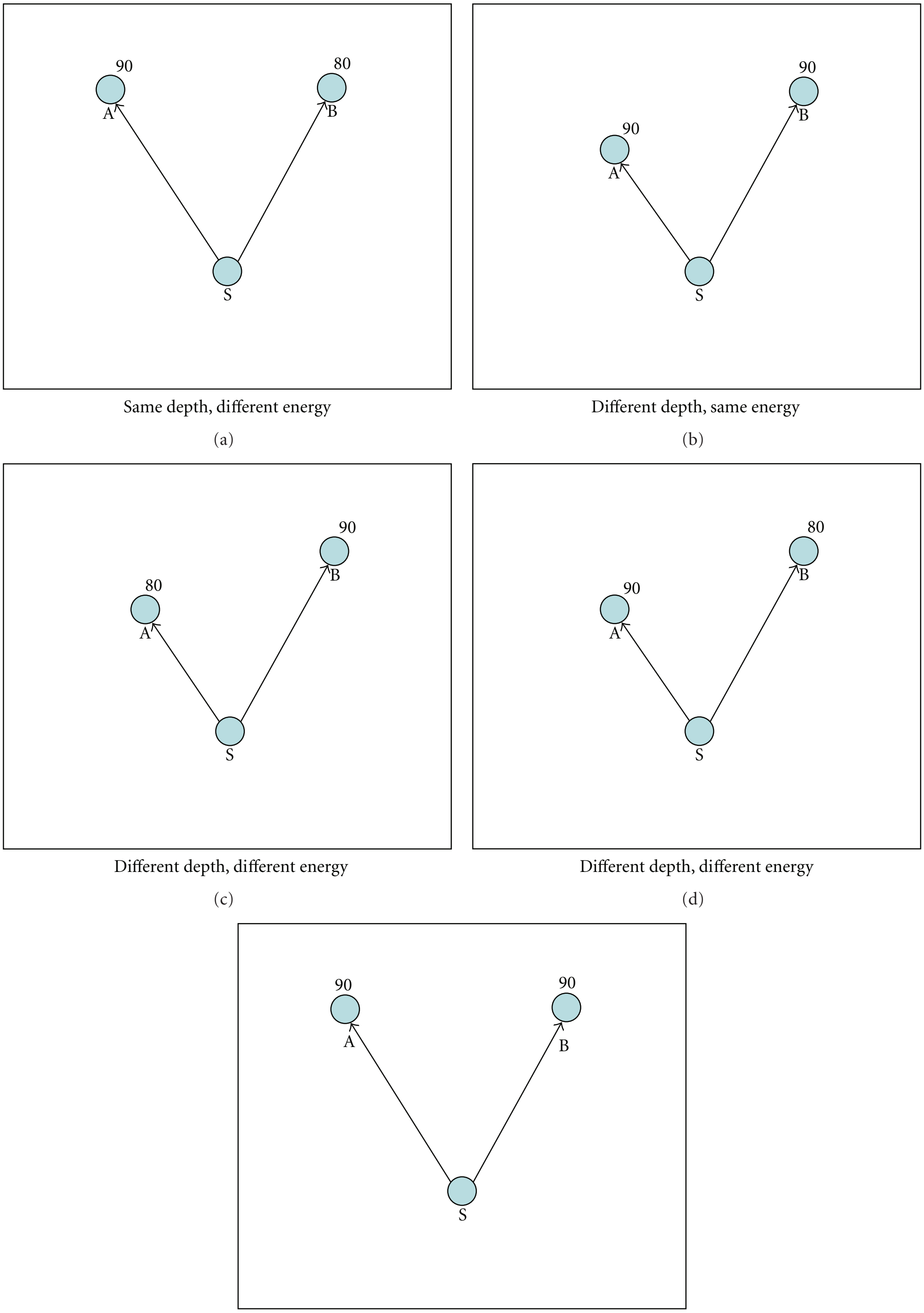
$$T = (1 - (\text{current energy}/\text{initial energy})) * \max\_\text{holding\_time} + p, \quad (1)$$

where max_holding_time is a system parameter (i.e., the maximum holding time a node can hold a packet), and p is the priority value.

The priority value is used to prevent multiple forwarding nodes from having the same holding time since the sensor nodes might have the same residual energy level. Therefore, if the holding time is only based on residual energy, the nodes having same residual energy will also have the same holding time. In such a case, the forwarding nodes will forward the packet at the same time. Hence, redundant packets will be transmitted. In order to avoid such redundant transmissions, the priority value is added to the holding time in order to make the difference among the holding times of the forwarding nodes having the same residual energy.

The priority value is computed as follows. The sending node sorts the forwarding list on the basis of the residual energy of the forwarding nodes. Upon receiving the data packet, the forwarding nodes add the priority value to the holding time based on their position in the list. The priority value is initialized with a starting value, and the priority value is doubled with the increase in the position index of the nodes in the list. Hence, due to the different positions in the list, the nodes have different priority values. Consequently, the nodes having the same residual energy will have different holding times even for the same packet.

Figure 4(e) illustrates the scenario where the forwarding nodes have same residual energy, and node S is the sender of



Same depth, different energy
(a)

Different depth, same energy
(b)

Different depth, different energy
(c)

Different depth, different energy
(d)

Same depth, same energy
(e)

Figure 4: Different possible scenarios during the forwarding of the data packet.

the packet, and node, A and B are the candidate forwarding nodes. The value 90 is assumed as the residual energy of the nodes A and B. As illustrated in Figure 4(e), both nodes A and B have the same residual energy. When these nodes receive the packet, they check their position in the forwarding list. On the basis of the position in the list, both the nodes compute the priority value. Let's assume that the nodes A and B are positioned at the second and third positions in the list and assume that the priority value is started with a starting value 10. Then, the priority value of node A will become 20, and node B will have the priority value of 40, because the priority value is doubled corresponding to the position in the list. Hence, despite of having same residual energy, both the nodes have different holding times for the same packet. Furthermore, since the difference between the holding times of both the nodes is double, a node has an enough holding time for overhearing the same packet from other sensor nodes. In contrast, in DBR, the difference between the holding times of the sensor nodes having similar depths is not long enough for overhearing. Hence, redundant packet transmissions are unavoidable in DBR. In EEDBR, the topmost node in the list has the highest priority because of having the highest residual energy among its neighbors. Therefore, we employ a holding time of zero for the topmost node in the list in order to reduce the end-to-end delay. The topmost node will forward the data packet as soon as it receives the data packet.

During the forwarding of the data packet on the basis of the depth and residual energy, different scenarios are possible as shown in Figure 4 where node S is the sender, nodes A and B are the forwarding nodes, and the values 90 and 80 are assumed as the residual energy values of A and B. Here, we describe how EEDBR responds to such scenarios. In case (a), both the nodes are having same depth. However, the sensor node A forwards the packet since it has more energy than node B. In case (b), both nodes have same residual energy. However, node B forwards the packet because it is located at the lower depth than node A. Similarly, in case (3), node B forwards the packet since it has more energy and also it is located at the lower depth. In case (d), node A forwards the packet because of having more energy. Here, it is also possible to give a priority to the node which has lower depth, which means it is nearer to the sink node. However, for the energy balancing purpose, the node having more energy is preferred. Finally, in case (e), since both the nodes have the same depth and the same residual energy, anyone can be selected for forwarding. As above-mentioned, both the nodes will have different holding times. Hence, one node will transmit the packet, and the other will suppress its transmission upon overhearing the transmission of the same packet.

In UWSNs, the suppressions of packet transmissions contribute to reducing the energy consumption, hence, improving energy efficiency. However, too much suppression of packet transmissions affects the delivery ratio. In some applications such as military surveillance, the delivery ratio is more important than the energy efficiency. Hence, in order to support such applications, we employ an application-based suppression scheme. In our suppression scheme, when the delivery ratio is less than a given delivery ratio threshold, the number of nodes which suppress their packet transmissions is reduced in order to meet the desired delivery ratio. During the forwarding of the data packets, the source includes the number of packets generated by that source. Upon receiving the data packets, the sink node computes the delivery ratio by dividing the number of data packets received at the sink to the number of data packets generated by the source node. If the delivery ratio is less than the desired delivery ratio based on the application requirement, the sink node informs the source node by sending/flooding a packet containing the delivery ratio at the sink. Consequently, the source node includes the delivery ratio value received from the sink into the data packet. Upon receiving the data packet, the forwarding node decides whether to suppress or transmit the packet based on the delivery ratio value in the data packet. Here, a probabilistic approach is used. The forwarding nodes generate a random number. If the random number is less than the delivery ratio value, the packet is transmitted without any suppression even if the same packet is received from other nodes. In this way, the degree of suppressions of packet transmissions is controlled. Hence, there is a tradeoff between the energy efficiency and the delivery ratio, and the proposed scheme, EEDBR, can be switched interchangeably based on the application requirement.

In EEDBR, the data packet's forwarding from a source node to a sink is summarized as follows. Each sender of the data packet includes a list of its neighboring nodes having smaller depths, called forwarding nodes. The list is ordered on the basis of the residual energy values of the forwarding nodes. Upon receiving the data packet, the first node in the list forwards the data packet immediately without waiting. The rest of the forwarding nodes in the list holds the data packet for a certain time computed using (1). During the holding time, upon overhearing the same data packet from another sensor node, the forwarding nodes generate a random number and compare it to the delivery ratio value received in the data packet. The nodes suppress the transmission if the random number is less than the delivery ratio. Otherwise, the data packet is transmitted. In case where no data packet is overheard during the holding time, the data packet is transmitted when the holding time expires. To illustrate further, the operation during the forwarding of the data packet is shown in Figure 5.

4. Performance Evaluation

In this section, we evaluate the performance of our proposed routing protocol, EEDBR, by comparing it to an existing routing protocol in UWSNs called DBR [8]. Since DBR is a representative localization-free routing protocol in UWSNs, we select DBR for the performance comparison.

4.1. Simulation Settings. Simulations were conducted using a commonly used network simulator called NS-2. We performed simulations with a different number of sensor nodes (i.e., 25, 49, 100, and 225). We employed grid and random topologies for the comparisons. In each topology, the transmission range of 250 meters was set for each sensor

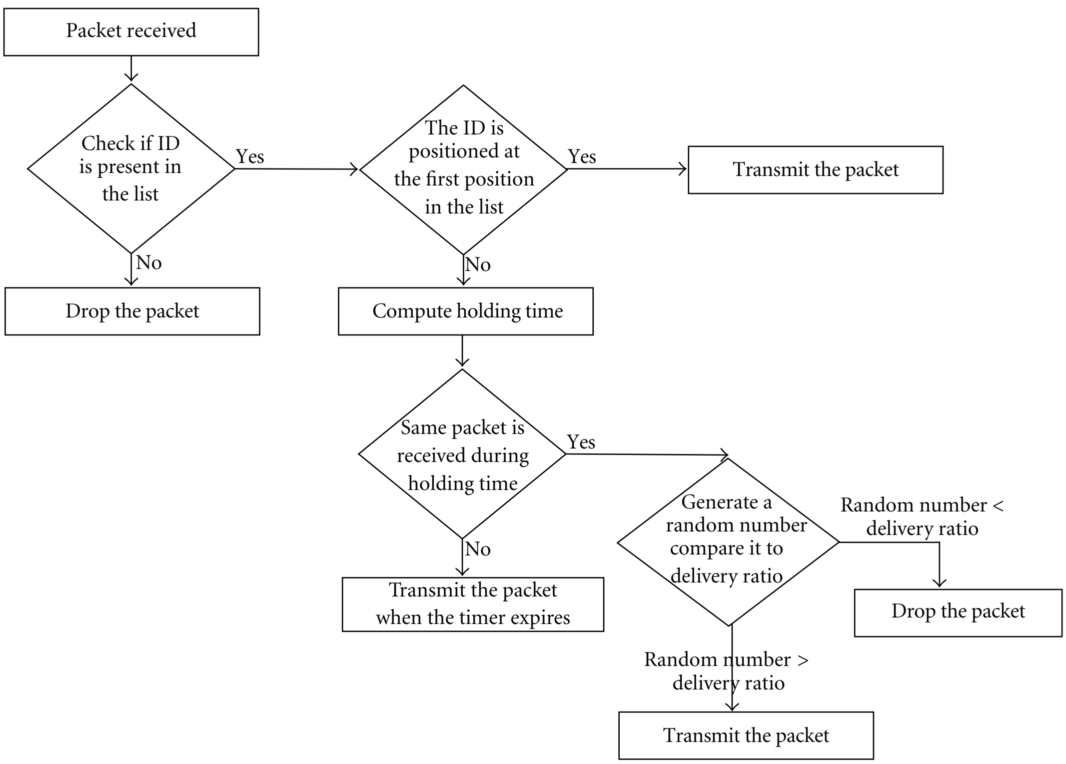


Figure 5: Operation at the forwarding node.

node. The initial energy value of 70 joule was set for all the sensor nodes. Different numbers of sink nodes were used for each topology (i.e., 2, 3, 4, and 6 sink nodes for 25, 49, 100 and 225 sensor nodes). In each topology, two source nodes were randomly selected from the bottom of the deployment region. Each source node generated a data packet of a size of 64 bytes every 15 seconds. The 802.11-DYNAV [12] protocol was used as an underlying MAC protocol. For all topologies, the results were averaged from 30 runs.

4.2. Performance Metrics. We used the following metrics for evaluating the performance of our proposed routing protocol.

Network Lifetime. Network life-time is the time when the first node dies in the network when the energy of that node is fully exhausted.

Energy Consumption. Energy consumption is evaluated through the total amount of energy consumed by the sensor nodes during the forwarding of the data packets from a source towards a destination/sink node.

End-to-End Delay. The end-to-end delay is the time taken by a packet to reach from a source node to a destination/sink node.

Delivery Ratio. Delivery ratio is defined as the ratio of the number of packets successfully received at the sink node to the number of packets transmitted from the source node.

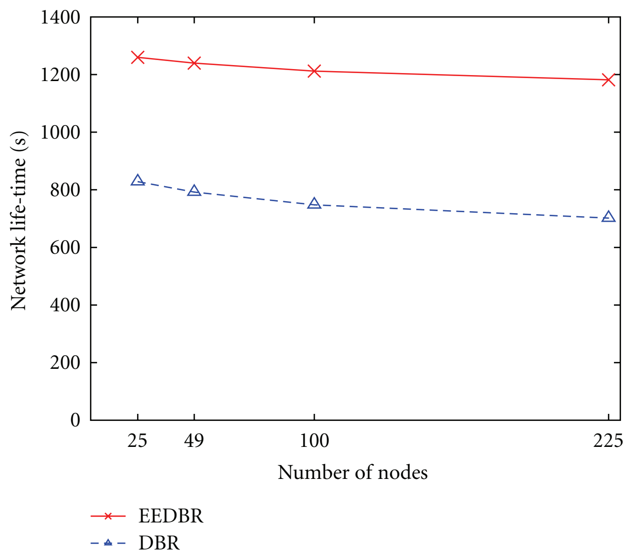


Figure 6: Comparison of network lifetime in random topology.

4.3. Simulation Results and Analysis

4.3.1. Network Lifetime. The network life-time of both the schemes in random and grid topologies is compared as shown in Figures 6 and 10, respectively. EEDBR shows improved performance over DBR. Since DBR selects the nodes having smaller depths to be frequently used for forwarding the data packets. Therefore, the energy of such nodes is exhausted rapidly, and these nodes die very soon. In

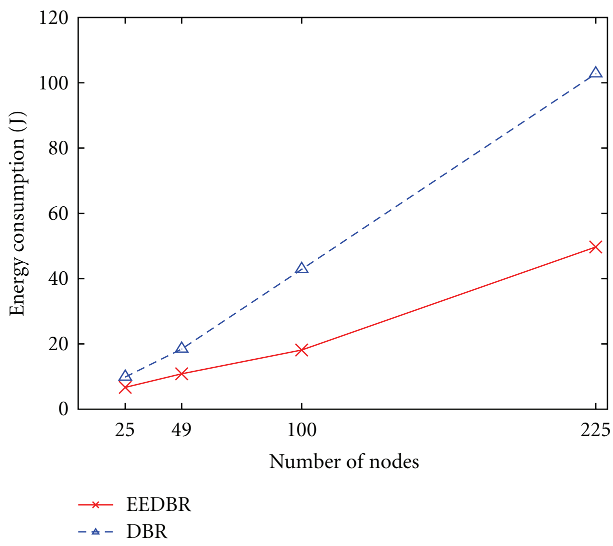


Figure 7: Comparison of energy consumption in random topology.

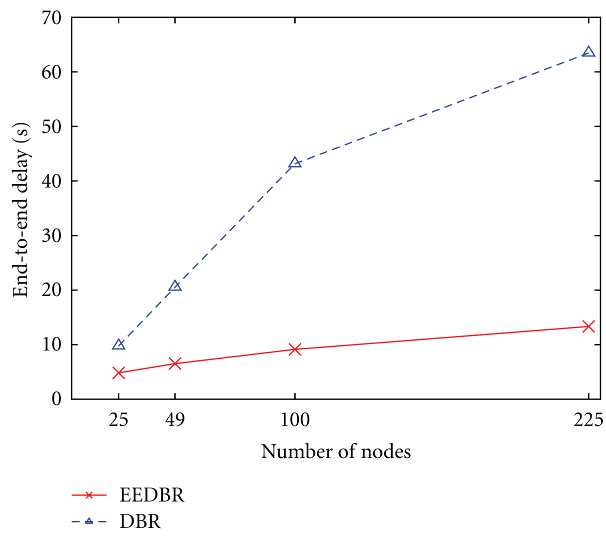


Figure 8: Comparison of end-to-end delay in random topology.

contrast, EEDBR employs the energy balancing among the sensor nodes in order to enable the sensor nodes to consume their energy parallely. Hence, the sensor nodes stay alive for long time. Furthermore, the lower energy consumption is another factor of the improved network life-time in the proposed EEDBR scheme. In EEDBR, a limited number of sensor nodes are allowed to participate in forwarding. The forwarding is not only restricted on the basis of the depth but also the residual energy of the sensor nodes. In addition, DBR cannot avoid redundant packet transmissions. The sensor nodes having similar depths also have similar holding times. Therefore, the same packets are transmitted at the same time in DBR. In contrast, in EEDBR, due to the employment of the priority values, the redundant transmissions of packets do not occur. Hence, the reduction in energy consumptions is achieved, which also improves the battery life-time of the sensor nodes.

4.3.2. Energy Consumption. Figures 7 and 11 shows, the energy consumption of both the schemes in random and grid topologies, respectively. The energy consumption of DBR is higher than the proposed EEDBR protocol due to excessive number of nodes' involvement in forwarding the data packet and redundant packets' transmissions in DBR as mentioned earlier. As shown in the figures, the energy consumption of both the schemes is increasing with the increase in network density. This is because more nodes become eligible for forwarding the data packet with the increase in network density. However, DBR only restricts the number of nodes on the basis of the depth of the sensor nodes. Only utilizing the depth of the sensor nodes can not reduce the number of nodes since sensor nodes have similar depths. In contrast, EEDBR restricts the number of nodes, based on two metrics: the depth and the residual energy. Furthermore, in EEDBR, due to the priority assignment technique, nodes have enough difference in their holding times. Therefore, the nodes holding a packet suppress their transmissions upon overhearing the transmission of the same packet form a high priority sensor node.

4.3.3. End-to-End Delay. The end-to-end delay of both the schemes is investigated as shown in Figures 8 and 12 in random and grid topology, respectively. In DBR, each sensor node holds the packet for a certain time proportional to the depth of the sensor node. Therefore, DBR has a long end-to-end delay. In contrast, EEDBR wants the first node in the list of forwarding nodes to transmit the packet as soon as it receives the packet. Therefore, the delay is reduced only to the propagation delay of the packet. As depicted in the figures in both random and grid topologies, the delay in DBR is continuously increasing with the increase in network density because the number of forwarding nodes also increases with the increase in network density. Since each node holds the packet for a certain time, the overall holding time of the packet also increases. The increase in network density does not affect the end-to-end delay in EEDBR, because each time the first forwarding node in the list has a holding time of zero.

4.3.4. Delivery Ratio. Figures 9 and 13 show the delivery ratio of both the schemes in random and grid topologies, respectively. The delivery ratio is much better in random topology than the grid topology, where the delivery ratio is higher than 94% for both the schemes in random topology. The delivery ratio is more than 90% in grid topology. However, when the network density reaches 225 nodes, the delivery ratio is abruptly dropped to 85%, since the number of collisions also increases with the increase in number of nodes. Relatively, DBR has better delivery ratio than EEDBR. The delivery ratio of DBR is 2 to 3% higher than EEDBR in random topology and 5 to 7% higher in grid topology. This is because DBR makes packets transmitted redundantly where multiple paths are followed to reach the sink node. Hence, the delivery ratio is high in DBR. However, the high

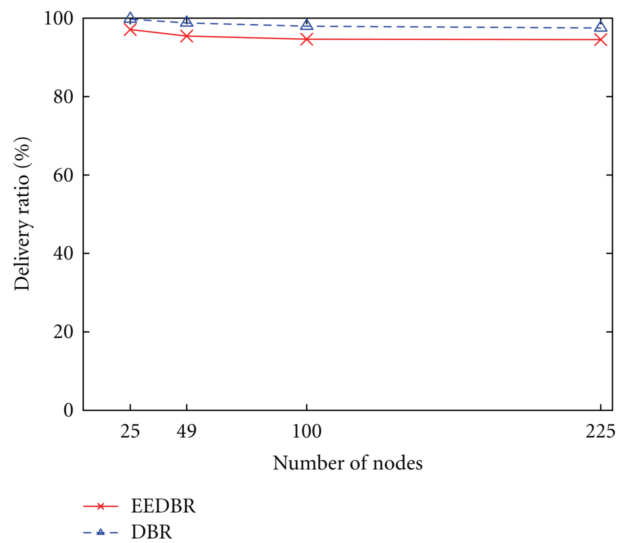


Figure 9: Comparison of delivery ratio in random topology.

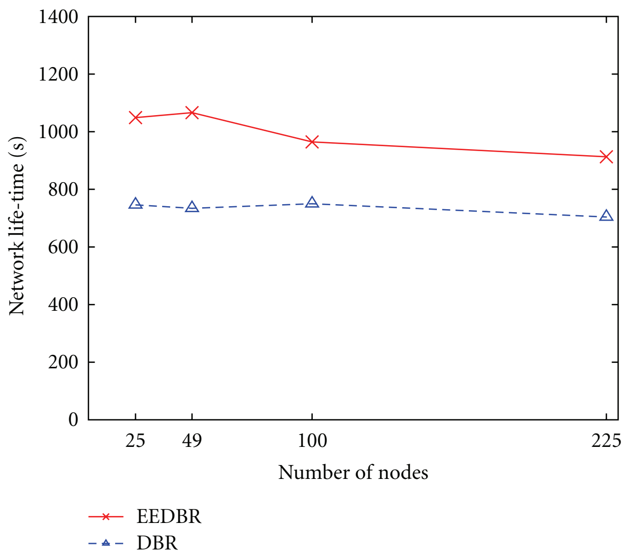


Figure 10: Comparison of network lifetime in grid topology.

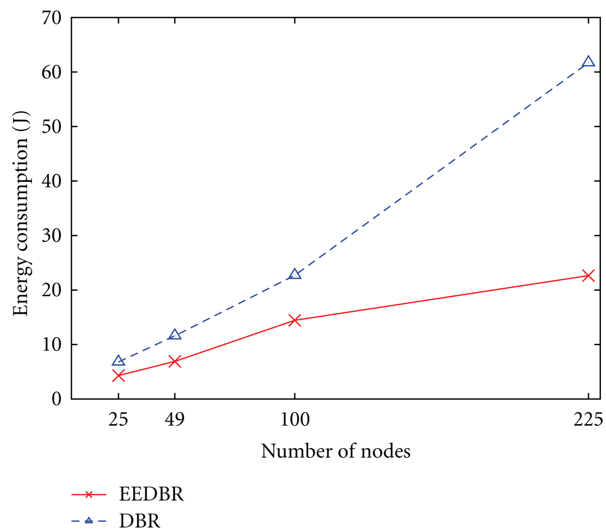


Figure 11: Comparison of energy consumption in grid topology.

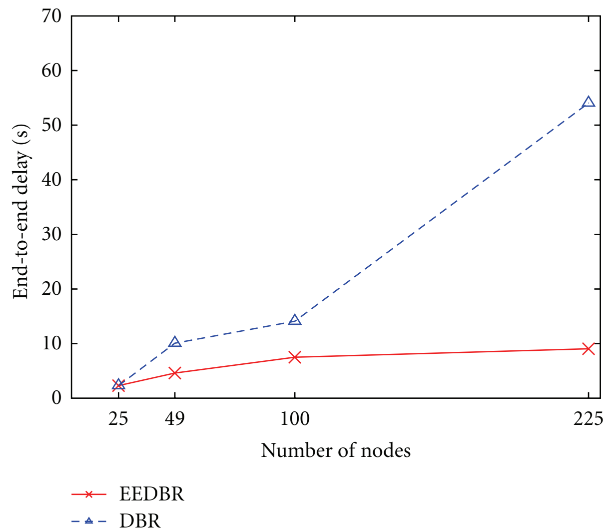


Figure 12: Comparison of end-to-end delay in grid topology.

delivery ratio in DBR is with the expense of excessive energy consumption and increased end-to-end delay.

5. Conclusions

Improving the energy efficiency in underwater wireless sensor networks (UWSNs) is one of the important issues, since the replacement of the batteries of underwater sensor nodes is very expensive due to harsh underwater environment. In this paper, we therefore proposed an energy efficient depth-based routing protocol (named EEDBR) for UWSNs. EEDBR utilizes the depth and the residual energy of sensor nodes as a routing metric. In particular, EEDBR does not require the localization of the sensor nodes which itself is a crucial issue in UWSNs. EEDBR employs a sender-based approach for routing where the sender decides a set of next forwarding nodes in order to reduce redundant transmissions from multiple forwarders. EEDBR has two phases, namely, knowledge acquisition phase and data forwarding phase. In the knowledge acquisition phase, each sensor node shares its depth and residual energy with its neighbors through *Hello* messages. In the data forwarding phase, each sender of the data packet includes a list of its neighboring nodes to the data packet. The set of the neighboring nodes called forwarding set/list is selected based on the depth of the neighboring nodes. Upon receiving the data packet, the forwarding nodes hold the packet for a certain time. The holding time is based on the residual energy of the forwarding nodes. Furthermore, we employed a novel suppression technique for the nodes overhearing the same packet. The degree of suppression of packet transmissions is controlled based on the delivery ratio which is notified by the sink node.

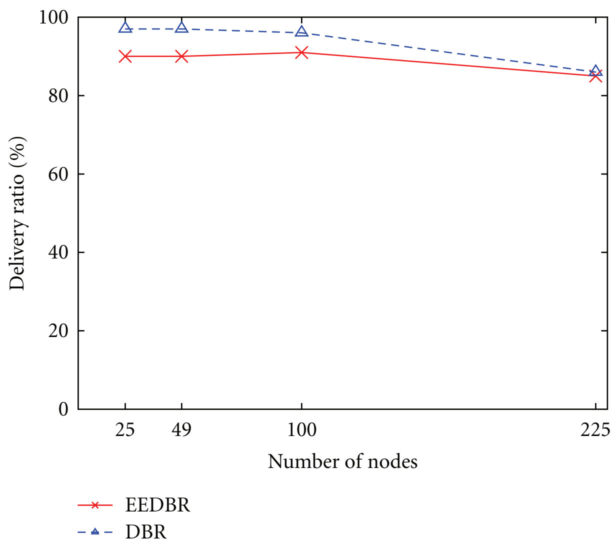


Figure 13: Comparison of delivery ratio in grid topology.

Through NS-2 network simulations, the EEDBR protocol was compared to a representative routing protocol in UWSNs called DBR [8]. Based on the comprehensive simulation, we observed that EEDBR contributes to the performance improvements in terms of network lifetime, energy consumption and end-to-end delay, while keeping the delivery ratio almost similar to the compared routing protocol.

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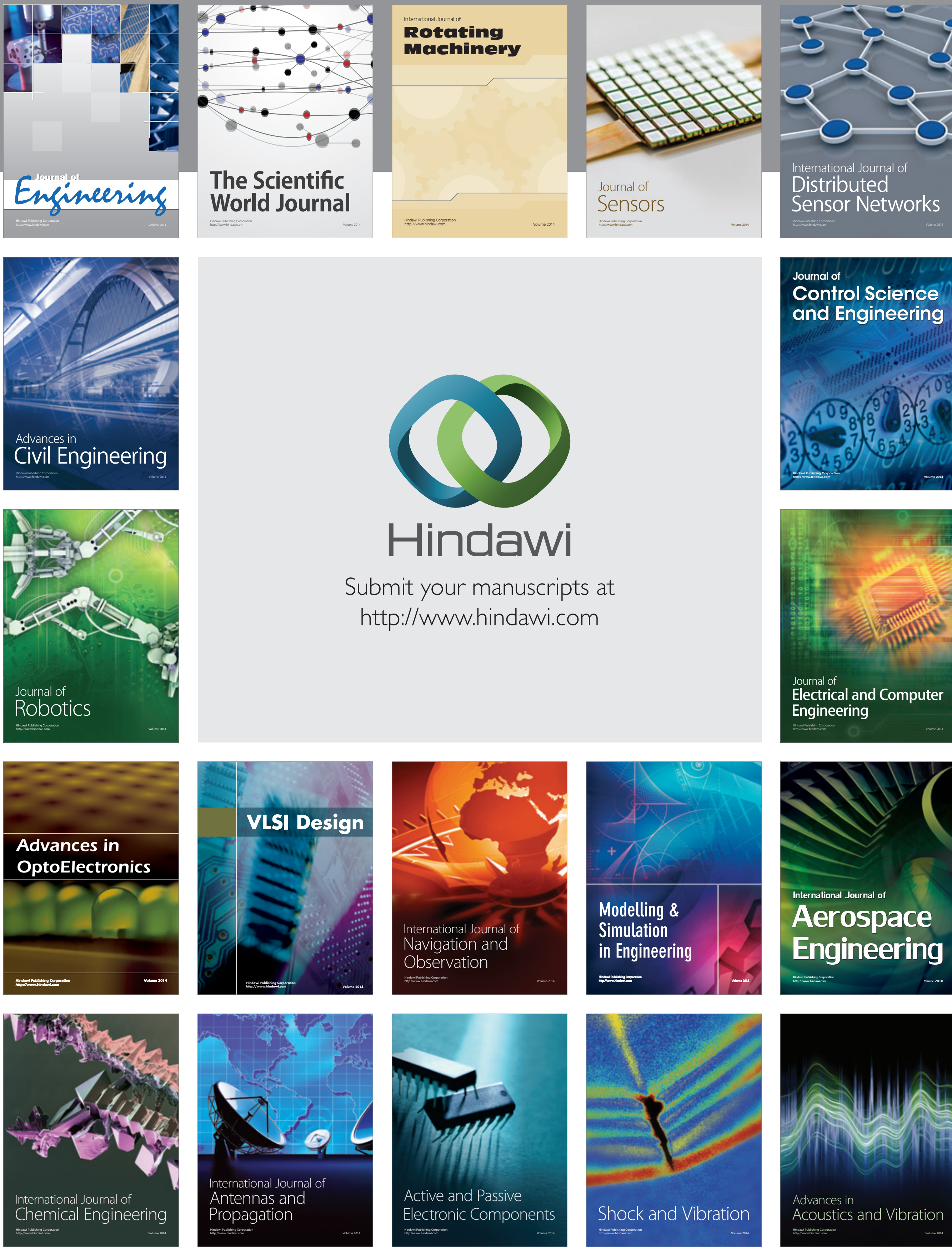
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