Turkish Journal of Electrical Engineering & Computer Sciences

http://journals.tubitak.gov.tr/elektrik/

Research Article

Turk J Elec Eng & Comp Sci
(2020) 28: 2303 – 2315
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doi:10.3906/elk-2001-51

A secure and energy-efficient opportunistic routing protocol with void avoidance for underwater acoustic sensor networks

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Received: 11.01.2020 • **Accepted/Published Online:** 04.05.2020 • **Final Version:** 29.07.2020

Abstract: Recently, underwater acoustic sensor networks (UASNs) have gained wide attention due to their numerous applications in underwater surveillance, oil leakage detection, assisted navigation, and disaster prevention. With unique characteristics like increased propagation delay, constant mobility of sensor nodes, high error rate, and limitations in energy and interference, efficient routing of data packets from the source node to the destination is a major challenge in UASNs. Most of the protocols proposed for traditional sensor networks do not work well in UASNs. Although many protocols have been specifically proposed for underwater environments, the aim of most of them is to improve only the quality of service (QoS) in the network. The security of the transmitted data, energy efficiency of the participating nodes, and handling of communication voids are three significant challenges that need to be adequately addressed in UASNs. In this research work, a secure and energy-efficient opportunistic routing protocol with void avoidance (SEEORVA) is proposed. This protocol uses the latest opportunistic routing strategy for reliable data delivery in the network and also provides priority to the nodes having energy above a specific threshold in the forwarding process, thereby increasing the lifetime and energy efficiency in the network. The transmitted messages are encrypted using a secure lightweight encryption technique. The protocol is also integrated with a strategy to handle the communication voids in the network. Simulation results with Aqua-Sim validate the better performance of the proposed system compared to the existing ones.

Key words: Energy efficiency, communication voids, routing protocols, secure data transmission, QoS, underwater acoustic sensor networks

1. Introduction

The ocean covers about 70% of the Earth's surface and is the most abundant source of rare and valuable resources. Due to various constraints, knowledge about the underwater environment is limited, and most of these resources are still unexplored. Underwater acoustic sensor networks (UASNs) [1] have given us hope as a possible solution to this problem. A UASN is a group of self-driven sensor nodes and autonomous vehicles connected underwater to perform different collective tasks based on user applications [2]. Sensor nodes placed at various locations and depths sense and record data and transfer them through the network of nodes to the

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destination sinks placed at the surface. The collection centers are usually on buoys or ships on the water's surface. Integrating with the most popular Internet of Things (IoT) [3, 4] technology, this smart network of interconnected underwater devices forms the Internet of Underwater Things (IoUT) [5].

Recently, the IoUT and UASNs have gained wide popularity due to their numerous research, industrial, and military applications. They are currently deployed for underwater monitoring and surveillance, oil leakage detection, assisted navigation, and disaster prevention. UASNs are different from the traditional sensor networks (TSNs) and use acoustic signals instead of radio signals. Routing of data packets in UASN is an exceedingly challenging task due to the unique features of the transmission medium such as long propagation delay, constant mobility of sensor nodes, high error rate, limitations in energy, increased error rate, interference caused by animals, and limited bandwidth. Reliable communication and efficient transfer of data from the source to the destination node are vital factors determining the success of various user applications deploying UASNs with multiple objectives. Routing protocols proposed for TSNs do not work well in the underwater environment [6–8]. In the last few years, many techniques have been discussed for efficient data transfer in UASNs, with opportunistic routing protocols (ORPs) [9, 10] being the latest and most efficient among them. ORPs use a broadcasting strategy to increase the number of forwarder nodes and create a prioritized list of available forwarder nodes. They then select the node that has maximum progress to the destination for forwarding the data packet. If that node is unable to forward the data packet within a specified time limit, the next forwarder node in the list forwards the data packet, thus ensuring reliable data delivery in the network. Although the ORPs proposed for UASNs offer several advantages, most of them are designed primarily for improving the quality of service (QoS) in the network.

One of the main limitations in UASNs is the difficulty in periodic recharging of the sensor nodes. If the energy available in the sensor nodes gets exhausted very quickly, the nodes cannot participate in future data transmission. Hence, it is essential to optimize the energy usage in data packet forwarding and conserve energy to extend the lifetime of each sensor node [11–13]. This issue is very inadequately addressed by most of the routing protocols proposed for UASNs [14–16]. Security in data transmission is another major issue to be addressed in UASNs. Sensor nodes in many military and industrial applications collect and record sensitive data. These sensitive data have to be securely stored and transmitted to the sink nodes and any leakage can be very harmful [17]. Moreover, it is found that numerous communication voids [18] occur in underwater environments. Communication voids occur when a source node is unable to find any suitable forwarder node in its transmission range and located in the direction of the destination. Communication voids are also called communication gaps or the unreachability problem. Failure of intermediate nodes due to energy drainage, wrong deployment, intrusions, attacks, etc. are some of the reasons contributing to the occurrence of voids in the network. As most of the latest routing protocols use a position-based greedy forwarding mechanism, this issue has become a major concern. Lack of proper mechanisms to handle voids can lead to huge data loss and loss of energy with retransmissions. Our proposed protocol, the secure and energy-efficient opportunistic routing protocol with void avoidance (SEEORVA), addresses all three issues and also supports good QoS for data transmission in the underwater environment.

In SEEORVA, the sensed and collected data are encrypted using a lightweight security protocol, the novel tiny symmetric encryption algorithm (NTSA) [19]. These encrypted packets are sent to the destination nodes through the network of sensor nodes. Only the collection and processing centers located at the surface are capable of decrypting these data packets, hence ensuring the security of transmitted data. The proposed protocol uses an opportunistic routing strategy but considers the remaining energy in each sensor node as a significant factor determining the section of the next best forwarder node. Nodes that have less energy are given less priority to participate in the forwarding process, thus extending the lifetime of each sensor node. SEEORVA is also integrated with a unique strategy to handle the communications voids in the network. Simulation results using Aqua-Sim [20] validated the better performance of SEEORVA compared to the existing protocols in the underwater environment.

The paper is arranged as follows. Section 2 presents the discussion on a few related works. Section 3 discusses the proposed work. Theoretical analysis of energy-efficient data transfer in the network is also presented. Section 4 presents a discussion on the results achieved through simulations. Here the performance of the proposed work is compared with existing protocols in the underwater environment. Section 5 presents the future research directions in UASNs. Finally, the paper concludes in section 6 with future research directions. Table 1 presents the notations and Table 2 presents the abbreviations used in the article. Table 3 lists the differences between TSNs and UASNs.

Table 1. Frequently used notations.

19 Notation	Definition
$\bar{x}$	Transmission signal coefficient
$\bar{h}$	Fading signal coefficient
$\bar{n}$	Noise coefficient
$y_1, y_2 \dots y_L$	Signal received at the receiving node
$\bar{y}$	Receiving signal coefficient
$\bar{w}$	Beamforming coefficient
B_f	Beamformer output
P_s	Signal power
P_n	Noise power
N_e	Effective noise at the output of beamformer
SNR_{B_f}	SNR at the output of the beamformer
$\bar{w}$	Beamforming vector

Table 2. List of abbreviations.

Abbreviation	Description
UASN	Underwater acoustic sensor networks
QoS	Quality of Service
SEEORVA	Secure and energy-efficient opportunistic routing protocol with void avoidance
IoT	Internet of things
IoUT	Internet of underwater things
TSN	Traditional sensor networks
ORP	Opportunistic routing protocols
NTSA	Novel tiny symmetric encryption algorithm
PDR	Packet delivery ratio
PFL	Priority forwarder list

Table 3. Difference between TSNs and UASNs.

TSN	UASN
Sensor nodes are deployed densely	Sparse deployment of sensor nodes
The Communication medium is radio waves	The Acoustic channel is the medium used
Data transfer rate is comparatively high	Data transfer rate is low
Less delay in data transmission	High delay is communication and data transmission
Lower energy consumption	High energy consumption
Higher number of static nodes	Higher number of dynamic nodes
Low error rate	High error rate

2. Related work

This section presents and discusses a few of the existing protocols proposed for UASNs. The security of the transmitted data, energy efficiency of the nodes, and handling of communication voids are three major challenges that need to be adequately addressed in UASNs. Several protocols are proposed to improve the QoS and energy efficiency in UASN. In Su et al. [21], a technique is discussed to increase the network lifetime of the sensor nodes in UASNs using the concept of Deep Q-Network. The technique is also aimed at reducing the delay in data transmission in the network. Another method [22] uses the fuzzy-based relay selection approach to select the node with the maximum energy for forwarding the data packets. Furthermore, the holding time is set for each group of forwarding nodes to avoid collision and save energy. Many protocols work on reducing the collision between the nodes in the network, like the multichannel MAC protocol discussed in Bouabdallah et al. [23]. Although many protocols have tried to improve the energy efficiency and QoS in UASNs, most of them have given very little importance to security in data transmission. A reliable security framework for UASNs is proposed in Ateniese et al. [24]. Common security measures and threats faced in UASNs are discussed in detail in that work. It aims to provide data confidentiality, integrity, and authentication for applications deploying UASNs. A comprehensive discussion on the security attacks faced in UASNs is presented in Shahapur and Khanai [25]. A technique to improve the secrecy of block transmissions based on the half-duplex nature of the underwater transceivers in underwater acoustic channels is presented in Huang et al. [26]. A few protocols are designed to handle the communication voids in the network [27, 28]. However, most of the existing protocols focus primarily on improving the QoS. Lack of an efficient technique for energy efficiency and void avoidance with adequate security in data transmission is still a major problem. The proposed method, secure and energy-efficient opportunistic routing protocol with void avoidance (SEEORVA), uses the latest opportunistic routing strategy for reliable data delivery in the network. The protocol considers only the nodes having energy above a specific threshold in the forwarding process, thereby increasing the lifetime and energy efficiency in the network. The transmitted messages are encrypted using a lightweight encryption technique and the protocol is integrated with a strategy to handle the communication voids in the network. The next section discusses the proposed method.

3. Proposed system

3.1. Theoretical analysis

In this section, the theoretical analysis of the proposed work in efficient energy utilization of a UASN is presented and discussed. Emphasis is given on optimizing the beamforming between the sender and the receiver nodes such that minimum energy is utilized during the transmission process. Here, assuming $\bar{x}$ as the transmission signal coefficient, $\bar{h}$ as the fading signal coefficient, $\bar{n}$ as the noise coefficient, and $y_1, y_2, \ldots, y_L$ as the signal received at the receiving node, the receiving signal coefficient $\bar(y)$ is given by

$$\overline{y} = \bar{h}\bar{x} + \bar{n} \tag{1}$$

Here the beamforming coefficient is assumed to be $\bar{w}$ such that

$$\bar{w} = \begin{bmatrix} w_1 \\ w\ \ 2 \\ . \\ . \\ w_l \end{bmatrix} \text{ and } \bar{w}^H = \begin{bmatrix} w_1^* & w_2^* & w_3^* & \ldots w_L^* \end{bmatrix}.$$

Combining the received signals with the beamforming coefficient $\bar{w}$, the beamformer output B_f is obtained as

$$B_f = \begin{bmatrix} w_1^* & w_2^* & w_3^* & \ldots w_L^* \end{bmatrix} \begin{bmatrix} y_1 \\ y_2 \\ . \\ . \\ . \\ y_L \end{bmatrix} \tag{2}$$

$$B_f = \bar{w}^H \overline{y} \tag{3}$$

Substituting the value of the received output signal $\overline{y}$ in Eq. 1 into Eq. 2, we obtain

$$B_f = \bar{w}^H \left(\overline{h}\overline{x} + \overline{n} \right) \tag{4}$$

$$B_f = \bar{w}^H \overline{h}\overline{x} + \bar{w}^H \overline{n} \tag{5}$$

Here the signal power P_s is given by $\bar{w}^H \overline{h}\overline{x}$ and noise power P_n is given by $\bar{w}^H \overline{n}$. Introducing constant P with signal power, we obtain

$$P_s = \left| \bar{w}^H \overline{h} \right|^2 .P \tag{6}$$

Now we have the effective noise at the output of beamformer, $N_e = \bar{w}^H \overline{n}$. Calculating the expectation E of N_e we have

$$N_e = E \left\{ \left| \bar{w}^H \overline{n} \right|^2 \right\} \tag{7}$$

$$N_e = E \left\{ \left(\bar{w}^H \overline{n} \right) \left(\bar{w}^H \overline{n} \right)^* \right\} \tag{8}$$

where $\bar{w}^H\overline{n} = w_1^* n_1 + w_2^* n_2 + \ldots + w_L^* n_L$ and $\left(\bar{w}^H\overline{n}\right)^* = w_1 n_1^* + w_2 n_2^* + \ldots + w_L n_L^*$

$$N_e = \mathrm{E}\left\{\sum_{\mathrm{i=1}}^{\mathrm{L}} |w_i|^2 |n_i|^2 + \sum_i \sum_j w_i w_j^* n_i^* n_j\right\}, \tag{9}$$

where i $\not\equiv$ j. Here $E\left(n_i n_j^*\right) = E(n_i)E(n_j^*)$, which will become zero. Thus the equation is reduced to

$$N_e = \sum^{|w_i|^2} E\{n_i\}^2 \tag{10}$$

$$N_e = \sigma_n^2 \sum^{w_i 2} \tag{11}$$

$$N_e = \sigma_n^2 \bar{w}^2 \tag{12}$$

$$N_e = \sigma_n^2 \bar{w}^H \overline{w} \tag{13}$$

Now the *SNR* at the output of the beamformer is given by

$$\underset{\max}{(SNR)} = \frac{\left|\bar{w}^H h\right|^2 P}{\sigma_n^2 \left(\bar{w}^H \overline{w}\right)} \tag{14}$$

The aim is to select the beamforming vector $\overline{w}$, such that $\overline{w}$ maximizes the *SNR* in multiple diversity receiving nodes,

$$\underset{\max}{(SNR)} = \left(\frac{\left|\bar{w}^H \bar{h}\right|^2}{\bar{w}^H \bar{w}}\right) * \frac{p}{\sigma_n^2} \tag{15}$$

Let us assume that the optimal $\overline{w}$ is K such that

$$\underset{\max}{(SNR)} = \left(\frac{K^2\left|\bar{w}^H \bar{h}\right|^2}{K^2 \bar{w}^H \bar{w}}\right) * \frac{p}{\sigma_n^2} \tag{16}$$

Here the constant K will get canceled, implying that scaling will have no effect. It is scale invariant and we need to select $\overline{w}$ such that its magnitude is one. Select $\overline{w}$ such that $||\bar{w}||^2 = 1$, which implies $\bar{w}^H \bar{w}$=1. Now

$$\underset{\max}{(SNR)} = |\overline{w}^H \overline{h}|^2 . \frac{p}{\sigma_n^2} \tag{17}$$

Now we need to find the maximum value for $\left(\left|\bar{w}^H \bar{h}\right|^2 \frac{p}{\sigma_n^2}\right)$, for which $\bar{w}$ = const $\bar{h}$. For this we have $c^2||\bar{h}||^2 = 1$, which gives $C = \frac{1}{h}\|$. Optimal beamforming vector $\bar{w}$ that maximizes the received $SNR = \frac{\bar{h}}{h} \| =$ $\bar{w}$ (the optimal value that is calculated as maximum ratio combiner). Now we have $SNR = \frac{\left(\bar{h}^H \bar{h}\right)^2}{h} \frac{p}{\sigma_n^2}$), which gives $SNR = h^2 \frac{p}{\sigma_n^2}$. This is the optimal *SNR* at the output of the receiver.

3.2. Best forwarder selection

The proposed method uses the opportunistic routing strategy for the selection of the best relay node. The opportunistic routing strategy enables the presence of more than one forwarder node and hence the chances of data delivery at the destination are high. Thus, our algorithm initially makes sure that the packet delivery ratio (PDR) in the network is high and maximum packets are delivered at the destination. The proposed algorithm used for the best forwarder selection is presented below. At first, the source node that has to transmit data packets creates a virtual vector pipe to the destination node. A list of nodes that are located within the pipe is then compiled. The highest energy of the nodes in the list is then calculated. The nodes that are outside the pipe are not considered in the forwarding process. A threshold energy value based on the calculated highest energy value is set for the forwarder nodes. The node that has energy above the threshold and within the transmission range of the source node and also that has the maximum progress to the destination is chosen as the best forwarder node. If this node cannot forward the packet within a specific period (set by a timer) due to reasons like mobility or damage of the node, the next node in the list forwards the data packet to the destination. Thus, a high rate of data delivery along with energy efficiency is guaranteed by the proposed approach. The working of this technique is illustrated in Figure 1. Here the source 's' wants to transmit the data packets to target node 't'. The source node creates a list 'f', 'c', 'h', 'a', 'b' of the nodes that are located within the vector pipe. Now the source node calculates the highest energy node among the four and sets the threshold value. Nodes 'h', 'c', and 'f' are within the transmission range of the source node. Therefore, a priority forwarder list (PFL) ('h','c','f') is generated by the source node based on the maximum progress to the destination. Let us assume that node 'h' does not have energy greater than the set threshold. Thus, the node 'c' is selected as the best forwarder. If the node 'c' is unable to forward the data packet within a particular time, node 'f' forwards it.

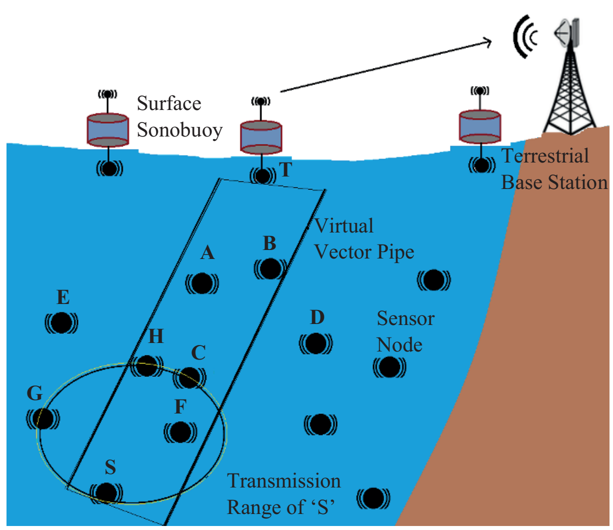

Figure 1. Illustration of the best forwarder selection algorithm using the proposed method.

Algorithm 1: For best forwarder node selection

1. The source node creates a virtual vector pipe to the destination node.
2. The source node checks for the nodes inside the pipe. If true go to step 3, otherwise drop the data packet.
3. Calculate the highest energy among the nodes inside the pipe and go to step 4

4. Set the energy threshold as highest/2.
5. The source node creates a PFL containing the nodes within its transmission range.
6. Sort the list by the distance to the destination. The node having a minimum distance to the destination is assigned the highest priority in the PFL.
7. Check whether the energy > threshold for all the nodes in the PFL. If true keep the node in the list and go to step 9. Otherwise, go to step 8.
8. Drop the packet and label as a low energy node.
9. Call packet forwarding algorithm.
10. Repeat the step until the packet reaches the destination.

Algorithm 2: For packet forwarding

1. Data packet is received by a source node.
2. The node generates the PFL.
3. Forward the packet to the nodes in the PFL.
4. If the best priority forwarder forwards the data packet within a period, go to step 6, else go to step 5.
5. Next node in the PFL forwards the data packet.
6. The received node repeats steps from 1 to 4 until the packet reaches the destination.

3.3. Security and void avoidance in data transmission

One of the major issues to be addressed in UASNs is the security of data transmitted between the sensor nodes. In many UASN applications such as military ones, the security of data is the most important factor. Any leakage of information in such applications can have major consequences. To provide high security for the transmitted data, we integrate a simple, lightweight, and strong encryption technique discussed in Rajesh et al. [19] into our proposed system. It is a symmetric encryption algorithm that follows the Feistel structure. The algorithm has 64 rounds and 32 cycles of operation. In every cycle, there is an odd and even round. The message to be transferred through the network is set as 64-bit blocks. The key used in the algorithm is 128 bits and is divided into 4 subkeys. The subkeys are then dynamically applied to odd and even rounds in encryption. This algorithm is used to encrypt the transmitted data packet, which can only be decrypted by the receiver, thereby protecting the data from intruders. Due to sparse deployment and frequent mobility of sensor nodes, communication voids are a major issue contributing to increased packet drops. An efficient mechanism to handle communications voids is necessary to guarantee good QoS for various applications in UASNs. In the proposed method when a node experiences a communication void, it sends a data packet void_alert to the previous node from which the data have come. The previous node tries to find an alternate route avoiding the void or around the void and routes the data packets to the destination. All the remaining packets through the void node are redirected to this new route until the void node reports that the void is past. This technique gives much better results compared to the major existing techniques used to handle communication voids. The major advantage of this technique is that it is easy to implement with less overhead and delay.

4. Results and discussion

The performance of the proposed method, SEEORVA, is analyzed and compared with that of the existing underwater routing protocols using simulations in Aqua-Sim [20]. Aqua-Sim is an extended version of NS-2 and offers easy implementation of underwater network scenarios. The specifications used for the simulation are presented in Table 4.

The protocols are compared in terms of performance using the packet delivery ratio (PDR) (number of packets delivered at the destination compared to the total packets sent), average end-to-end delay, and normalized energy consumption. The PDR and average end-to-end delay are used to measure the QoS in the network. The number of nodes participating in the network is varied and the performance of the protocols is measured. Comparison is done using vector-based forwarding (VBF) [29] and vector-based void avoidance (VBVA) [30] protocols. Figure 2 presents the comparison of PDR with a varying number of nodes. Here we can see that the proposed technique has a better PDR compared to all the existing techniques with different numbers of nodes. Moreover, in void scenarios the proposed technique achieves a good PDR. This is because, in the proposed technique, the best forwarder is selected using an opportunistic strategy and even if the best forwarder is unable to forward the data packet, the next best forwarder forwards it, thus ensuring reliability and a high packet delivery rate in the network. Figure 3 presents the comparison of average end-to-end delay with varying number of nodes. SEEORVA has less delay in data transmission compared to all other existing techniques like VBF and VBVA. The proposed technique is easy to implement with less complexity. The efficient forwarder priority list in the algorithm aids in less delay in data transmission. Figure 4 presents the normalized energy consumption achieved through various protocols with varying numbers of nodes in the network. It is evident that SEEORVA has better energy efficiency in the network compared to the existing approaches. In addition, the proposed technique is tested in a communication void environment. Both in normal and void scenarios, the proposed technique achieves much better energy efficiency compared to all the existing approaches. This is because the proposed technique considers the residual energy available in the sensor nodes for the forwarder selection process. Thus, the network lifetime is extended with improved energy efficiency in the routing process. The simulation results show the better performance offered by the proposed technique in terms of QoS, energy efficiency, and security compared to the existing techniques in UASNs.

Table 4. Simulation specifications.

Parameter name	Values
Simulator name	NS 2.35 with Aqua-Sim
Dimension of topology	1500 x 1500 x 1500 m
Transmission range	250 m
Antenna-Type	Omni-Directional
Data rate	50 kbps
Packet size	25 to 125 bytes
Number of nodes	100 to 300
Simulation time	200 s
Number of Simulation runs	10
Protocols	SEEORVA, VBF, VBVA

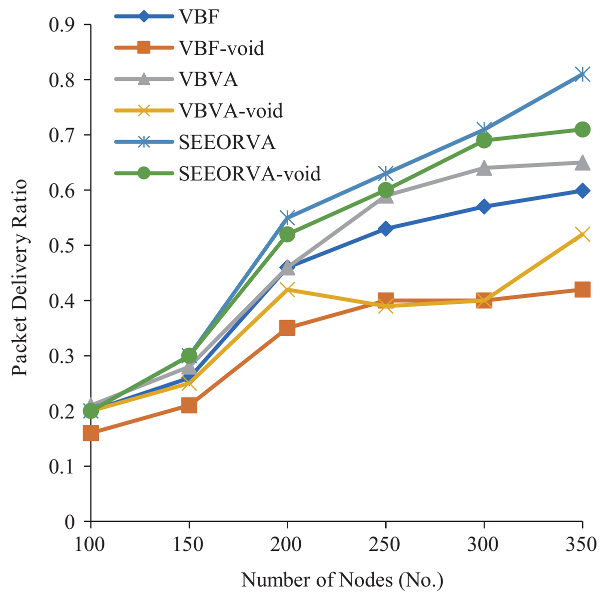

Figure 2. Variation in packet delivery ratio (PDR) with different numbers of nodes.

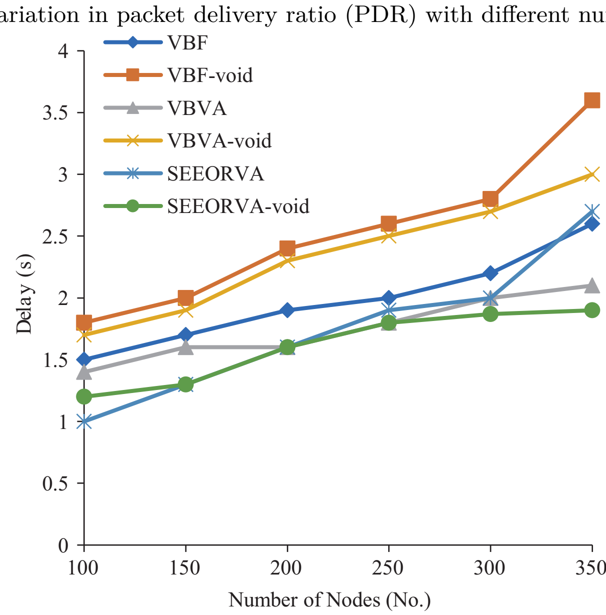

Figure 3. Variation in delay with different numbers of nodes.

5. Future research directions

In this section, we list a few research areas within UASNs that have generated interest among researchers due to the opportunities, issues, and challenges.

- Quality of service: QoS has been one of the major research areas focused on in UASNs. As the success of most of the applications depends on a high delivery rate, less delay, and other QoS parameters, numerous studies have been carried out in this direction. With an increased number of sensor nodes and advancement in sensor technology, new technique for further optimization of QoS in the network is an emerging area of research.
- Energy efficiency: With restrictions and limitations in recharging the deployed sensor node underwater,

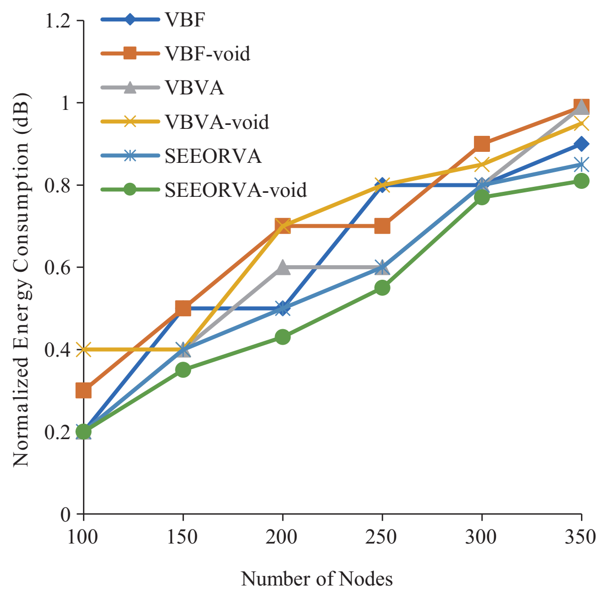

Figure 4. Variation in normalized energy consumption with different numbers of nodes.

the major hindrance behind the success of many applications is related to energy efficiency. Current research focuses on optimizing energy usage in the routing process and preventing energy leakages. This will be a major area of research in the future too.

- Channel utilization: Efficient utilization of the channel is another major area of research in UASNs that has gained wide prominence. With numerous challenges like propagation delay, constant mobility of sensor nodes, high error rate, and interference, it is vital to have optimal utilization of the channel.
- Security: The security of data transmitted between sensor nodes is a major area of concern. In many UASN applications such as military ones, the security of data is the most important factor. Any leakage of information in such applications can have major consequences. Recently, numerous studies have been carried out to secure the communication between the sensor nodes in UASNs. With increasing attacks and threats, research in security and privacy will be an ongoing and highly challenging task.
- Reliability: Many studies have focused on reliable data delivery in the network. This is an important parameter because it provides trust for user applications and helps in its success.
- Communication voids: Sparse deployment and frequent mobility of sensor nodes have led to increased communication voids in networks, leading to frequent packet drops. An efficient mechanism to handle communications voids is necessary to guarantee good QoS for various applications deployed with UASNs. This is a major research area in UASNs and will continue to be prominent in the coming years.

6. Conclusion

The security of the transmitted data, energy efficiency of the nodes, and handling of communication voids are three major challenges in UASNs that are not adequately addressed in most of the existing protocols. To address these issues, a secure and energy-efficient opportunistic routing protocol with void avoidance (SEEORVA) is proposed. This protocol uses the latest opportunistic routing strategy for reliable data delivery in the network and considers only the nodes having energy above a specific threshold in the forwarding process, thereby increasing the lifetime and energy efficiency in the network. The transmitted messages are encrypted using a lightweight encryption technique and the protocol is also integrated with a strategy to handle the communication voids in the network. Simulation results with Aqua-Sim confirmed the better performance of the proposed system compared to the existing ones. The proposed technique needs to be tested in a real-time underwater environment in the future. The design could also be modified to incorporate bulk data coming from numerous sources.

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