Reliability in IoUT enabled underwater sensor networks using dynamic adaptive routing protocol

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Abstract: Network lifetime is identified as the most crucial parameters in under water wireless sensor networks (UWSN) in Internet of underwater things (IoUT) applications. Other challenges include: limited bandwidth, high attenuation, high path loss, limited battery life etc. The main focus of this paper is to consider a trade-off between the energy consumption and network lifetime. This paper proposes an optimal routing protocol called the energy dynamic adaptive routing (DAR) protocol. The DAR protocol maintains a trade-off between the reliability or packet delivery ratio (PDR) of sensor nodes and bit error ratio (BER) using an optimal dynamic adaptive routing approach. An optimal directed acyclic graph (DAG)-based route selection is exploited to select the neighbour and successor nodes. The cost function with a directed acyclic graph is utilised for better transmission of packets. The experimental results with BEAR show that the proposed method deals with the issues raised in the conventional protocol and improve the reliability of packets with higher BER.

Keywords: under water sensor network; UWSN; internet of things; directed acyclic graph; DAG; dynamic adaptive routing; DAR.

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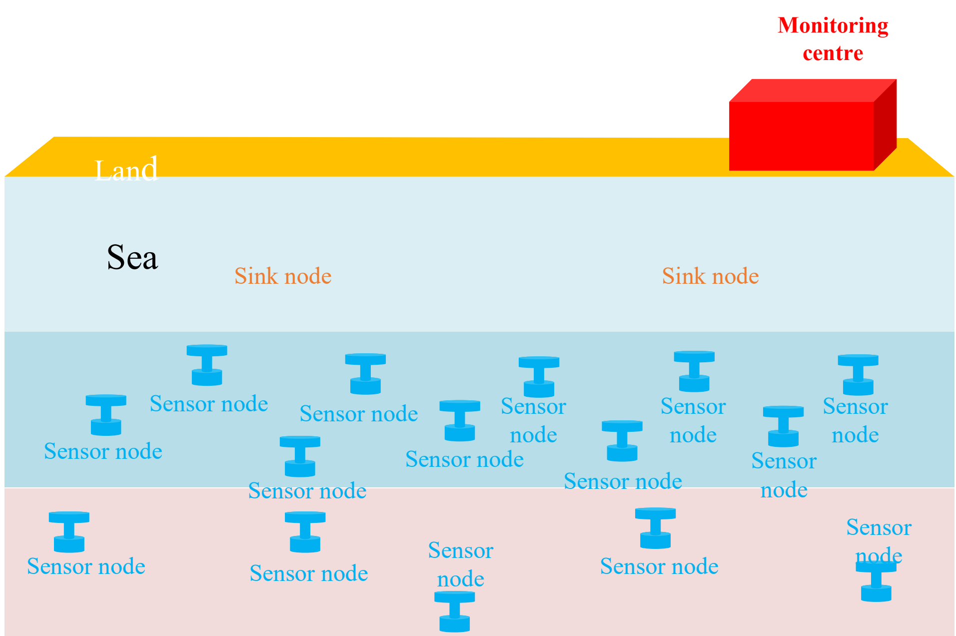
1 Introduction

The rapid devolvement in embedded electronics and wireless technology and interest in wireless sensor networks (WSNs) have been on the rise. The WSNs consist of nodes with limited computational capability and power due to smart sensors and embedded CPU.

The sensors make the nodes monitor several factors like vibration, pressure, heat and humidity. The WSN node has a computing unit, sensor interface, power and a transceiver unit. The sensor nodes perform a more critical task, which makes the nodes communicate with each other to transmit the data between the sensors. The communication takes place mostly in a distributed environment and hence a centralised network is needed to improve the communication between the nodes in WSN. This has led to the adoption of the internet of things (IoT), which provides fast access and high feasibility for environmental data. This could ensure higher efficiency, processing and productivity (Kocakulak and Butun, 2017). The most important element in IoT is WSN and this helps to provide common services and collaborates with it when it works as a remote access heterogeneous system in ad hoc environments. Integration of IoT with WSN is not just speculation, but it is supported by international companies and ensures better development and testability of the system. It helps to link the data generated by the sensor nodes with messaging features, social networks and web-based services (Alcaraz et al., 2010).

The UWSNs are used over a wide range of applications specifically for monitoring and other facilitations. It offers a promising solution over conventional demanding applications. Though UWSN applications offer exciting range of advantages, it suffers from various challenges. The main reason behind such challenges is due to unpredictable conditions due to the availability of sensor nodes in water environment that leads to serious constraints in its design and deployment. The deployment of sensors in UWSN becomes harsh due to unpredictable nature of underwater. The present technology allows constrained communication but it seriously fails to incur significant deployment cost, device recovery and maintenance to cope with unpredictable conditions of underwater.

Figure 1 Network architecture of UWSNs (see online version for colours)



The selection of model shows in Figure 1 is due to following reason. In underwater unpredictable communication, the communication medium is underwater and hence communication protocols get void in underwater terrestrial sensor network. The acoustic signals are used mostly in underwater communication in case of longer distances. On other hand, the radio communication is used for shorter distance underwater communication. However, the transmission over longer distance using radio signals needs extra low frequencies with high transmission power and larger antennas. This reduces the lifetime of network in underwater WSN. On other hand, the propagation delay is extremely high than RF communication. Hence, it is very necessary to use effective routing protocols in UWSN than terrestrial WSN.

Routing is an important factor of WSN communication, which enables effective communication by sharing the information between the nodes in the UWSNs. However, it is noted that no routing protocols exist in UWSNs and hence the main focus of this paper is to provide a trade-off between the network lifetime and energy consumption, which is estimated in terms of single to noise ratio, bit error rate and packet delivery ratio (PDR).

The contribution of the paper is presented as follows:

- In this paper, an optimal routing protocol is proposed, which adopts a dynamic adaptive routing method.
- This DAR protocol is designed to maintain the trade-off between the reliability of packets in underwater sensor nodes (PDR) and network lifetime (SNR, BER), using an optimal dynamic adaptive routing (DAR) approach.
- Three different phases have been used, namely: initialisation, dynamic routing and transmission to operate the entire mechanism.
- Further, the routing is established using an optimal directed acyclic graph (DAG) dynamic routing phase that helps to select the route between the neighbour and successor nodes.
- The authors have facilitated the successive routing for packet transmission from one node to another.
- Finally, the cost function with the DAG is utilised to find the nodes with higher residual energy for better transmission of packets.

The outline of the paper is presented as follows: Section 2 surveys the related works. Section 3 provides the system model and Section 4 discusses the proposed protocol. Section 5 reports the simulation results and Section 6 discusses the effectiveness of the proposed method. Finally, Section 7 concludes the paper with future work.

2 Related works

Many underwater WSN protocols have been proposed in conventional methods, some of which are discussed in this section. This includes avoiding a void node with adaptive hop-by-hop vector-based forwarding (Javaid et al., 2017a, 2017b), where the sensor nodes are allowed to forward the packet in multi hop fashion inside a virtual pipeline. The sensor nodes lying outside the virtual pipeline fails to forward the packets, which avoids network flooding. 3D-based UWSN deploy with heuristic-based mixed integer linear program optimisation (Khalfallah et al., 2016) that monitors the quality and connectivity of the deployed UWSN. A two-dimensional underwater barrier deployment algorithm (Khalfallah et al., 2015) that guarantees better detection of barrier like chemical pollutants with reduced deployment cost. The total number of sub-areas is minimised using integer linear programming algorithm. A convex optimisation problem with one-step least-square method (Yan et al., 2012) is modelled in underwater source in the presence of noise and utilises the energy of each sensor to find the location of source. Similar to Yan et al. (2012), the technique in Dong et al. (2017) uses median and reversed reverse localisation scheme, which is accurate in finding the paths using median RLS. Apart from this, there are several energy efficient algorithm that operates on routing algorithm. This includes energy efficient depth-based routing and depth-based routing (Mahmood et al., 2014), dynamic sink mobility equipped depth-based routing (Khan et al., 2015), scalable and efficient data gathering routing protocol (Ilyas et al., 2015), ARCUN (Ahmed et al., 2015), the error control and adjustment method (Han et al., 2018), an energy efficient chain-based routing protocol (Rani et al., 2017), the slotted CSMA-based reinforcement learning approach (Jin and Huang, 2013), a fault-resilient localisation scheme (Das and Thampi, 2017), a proactive opportunistic forwarding mechanism (Liu et al., 2017), cross-layer protocol stack development (Dhongdi et al., 2017), multi-hop mechanisms (Cheng and Li, 2017), data aggregation protocols (Goyal et al., 2017), a topology control algorithm for signal irregularity (Liu et al., 2015), constrained surface-level gateway placement (Li et al., 2010), highly selective and fitness protocols (Zenia et al., 2016), forward error correction (Domingo and Vuran, 2012), maximum coverage algorithms (Akkaya and Newell, 2009), a diagonal and vertical routing protocol (Ali et al., 2014), a connected dominating set (Senel et al., 2015), energy efficiency distributed time synchronisation algorithms (Li et al., 2013), level-based adaptive geo-routing (Du et al., 2014), adaptive reliable transport (Cai et al., 2013b), integer linear programming (Ibrahim et al., 2013), the node architecture low-cost realisation method (Lu et al., 2008) and vector-based forwarding-network coding (Cai et al., 2013a) and an energy efficient, interference and route aware protocol (Khan et al., 2016) which forwards the data to its neighbouring node to increase the network lifetime.

All of the above methods provide data reliability, energy efficiency and secured routing in underwater sensor networks. However, to the best of our knowledge, the use of IoT to improve the communication between the sensor nodes has not been addressed, which is the core aim of the proposed method.

3 System model

The reliability of links on underwater IoT communication has been estimated using a channel model, which is placed in an underwater scenario. The main aim of the model is to estimate successful delivery of packets over each UWSN link. The successful delivery of packets to the destination node estimates the packet reliability and this is considered to be advantageous for modelling a reliable protocol for communication using the internet of underwater things (IoUT) model. There are several elements in the underwater channel model, where the channel is divided into two main parts. Initially, the relationship between transmitting power and SNR is modelled and then the relationship between PDR and SNR is modelled. This helps to calculate the reliability of the packets transmitted over IoUT links.

3.1 Relationship between transmission power and signal to noise ratio

The main aim is to find the relationship between SNR and the transmission power. Here, the SNR is divided based on four regions, namely: source, transmission loss, directivity index and noise level, which is given by,

$$\gamma_{dB} = S_{level,dB} - T_{loss,dB} - N_{level,dB} + D_{index,dB} \tag{1}$$

The SNR is thus expressed as,

$$\gamma = S_{level} - T_{loss} - N_{level} + D_{index} \tag{2}$$

The relationship between the SNR (γ) and transmitter power (P) is thus expressed as:

$$\begin{aligned} \gamma &= 10\log(P) - \log\left(4\pi r^2\right) - \log\left(0.67\times 10^{-18}\right) - 20\log d \\ &- \left[\left(\frac{0.11f^2}{1+f^2}\right) + \left(\frac{44f^2}{4{,}100+f^2}\right) + 2.75\times 10^{-4} f^2 + 0.003\right] d\times 10^{-3} + 18\log f \end{aligned} \tag{3}$$

3.2 Relationship between signal to noise ratio and PDR

The second goal of the channel model is to estimate the PDR over IoUT. To achieve this, the modulation is chosen as BPSK modulation and a Rayleigh fading channel is used for signal propagation, which supports the multipath effect in shallow and deep water. Based on this, the BER of BPSK is derived as,

$$BER(\gamma) = 0.5\left(1 - \sqrt{\frac{10^{0.1\gamma}}{1+10^{0.1\gamma}}}\right) \tag{4}$$

For a given SNR (γ), the PDR with size m bits is estimated as,

$$\begin{aligned} P_{success}^{m}(\gamma) &= [1 - BER(\gamma)] \\ P_{success}^{m}(\gamma) &= \left(0.5 + 0.5\sqrt{\frac{10^{0.1\gamma}}{1+10^{0.1\gamma}}}\right)^{m} \end{aligned} \tag{5}$$

4 Proposed protocol

The network has multiple sensor nodes and each node has an overview on entire topology of the network. Each node has the ability to compute two DAG, where the former one is computed for destination and latter for forwarding the entries to the destination node. The packets from source node are assumed to be forwarded through the forwarding nodes and the packet is transferred from source to destination without packet dropping. The graph employed for the purpose of routing is always carried using an overhead bit in each header of the packet. Additionally, there exists an additional bit that carries the information about forwarding packets. The packet header is responsible for forwarding or routing the packets. If there are no forwarding edges, the packet is transferred to other

DAGs. Similarly, the packet header is also transferred to neighbouring DAG or else the packet is dropped.

The proposed protocol uses three phases to provide successful delivery of packets, namely: initialisation, tree construction and transmission phase, which are outlined below

4.1 Initialisation phase

In this stage, the sink node broadcasts the packets to inform the other nodes regarding the total available nodes and then it gives information about the start and stop time of the initialisation phase. The nodes further estimate the following:

- comparative location
- comparative distance from the sink node
- identification of the sector where the nodes are located.

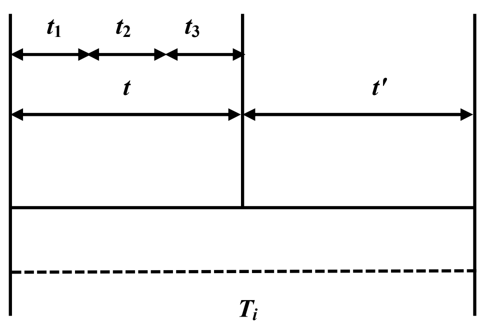
4.2 Tree construction phase

In this stage, the construction of the tree is done in two stages. Initially, the entire node finds the neighbour node and, finally, it chooses its successor to facilitate the nodes from its neighbourhood nodes.

4.2.1 Neighbour finding

At this stage, the lower depth node is searched within its sector and the root node is established towards the sink. The nodes are allocated with a time slot based on the sink for better communication, e.g., a four-way handshake time slot.

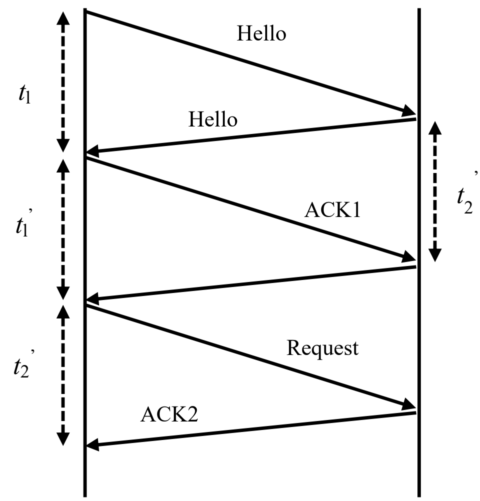
Figure 2 Four-way handshake time slot



The time slot (T_i) is divided into two segments with a maximum length equal to a four way handshake. Here, the deployment of the node is done in a random way and hence the node does not have a neighbour and during that instance, a second time slot (t') is used for discovery of neighbours. The entire process is shown in Figure 3.

Initially, a broadcast hello packet is sent with the transmission range or the threshold range within the sector. The nodes lying inside the range reply with an ACK1 message and provision for a node is made to select only one neighbour from the sector of the next hop that lies at a lower depth (Figure 3). Once the ACK1 is received, node *i* broadcast the neighbour request near nodes which have replied with the ACK1 message. Further, intended node accepts and acknowledges an incoming request from the ACK2 packet. This is done while the identity of the sensor node is recorded within its sector. Once the ACK2 is received, the identity of neighbouring node is stored and response is made with the help of ACK2 message and this response message is sent to the sink node with a handshake signal.

Figure 3 Mechanism of handshaking method



4.2.2 Optimal energy efficient path

In the DAR protocol, the entire communication is overseen by the descendant and helping nodes. Hence, the main task is to select the descendant and helping nodes, since this consumes less energy for transmission. Consider a cost function (Q_{ij}) when a node i communicates with node j, then the cost function is given by,

$$Q_{ij} = a \times d(i, j) + (1 - a) \times d(j, sink) \tag{6}$$

where

$d(i, j)$ defines the distance between nodes i and j

$d(j, sink)$ defines the distance between the sink and node j.

The cost function is calculated by the broadcasting function for the neighbour nodes. After the estimation of the cost function, the cost function is sorted out in ascending order, where the node id belonging to the 1st value is considered as the descendent node and the node id belonging to the 2nd value is considered as the helping node.

At each round, the distance from the sink is estimated by the broadcast node and when the distance is less than the transmission range, the packet is transmitted directly to the sink. On the other hand, when the node lies outside the sectoring range, then the comparative energy of the descendant node is checked with the average comparative energy and if the value of comparative energy is greater than the average comparative energy, then the packet is transmitted to the descendant node. In case the second checking of distance fails, the comparative energy of the helping node is checked by the broadcast node and it transmits the data packets to the helping node. However, if the node lies inside the range, it is transmitted directly.

4.3 Transmission phase

The distance of the broadcast node is checked at regular intervals from the sink and when it is less than the threshold range, direct transmission is possible towards the sink. On the other hand, when the distance is greater than the threshold range, then the comparative energy of the next node is checked. When the energy of the neighbour node is greater than average comparative energy, the successor receives the packet. However, when there is a failure in the second check, the comparative energy is estimated by the broadcast nodes and upon meeting the required condition, the packet is transmitted towards that node or it is broadcast directly over the sink.

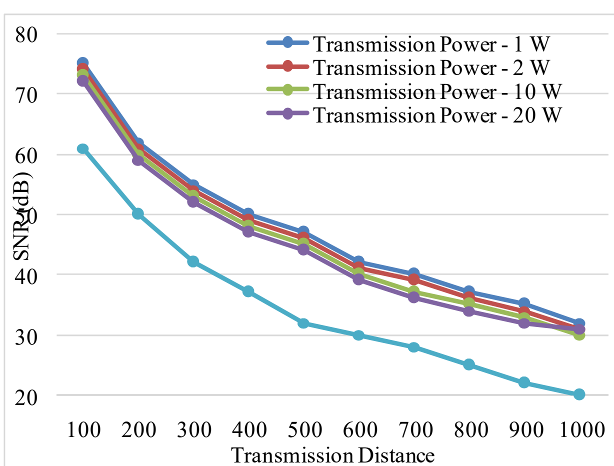
5 Results

The performance evaluation was conducted using C++ and the underwater sensor was simulated over the Rayleigh Fading channel using BPSK modulation. The parameter was set and the transmission power was set between 1–30 W and the frequency was set as 10 KHz and the packet size was set as 3 KB. Finally, the performance metrics were measured in terms of SNR, BER and PDR.

5.1 Evaluation of SNR

The results of SNR are shown in Figure 4, which plots the BER as a function of distance, which varies between 100 m and 1,000 m and the transmitter powers are set between 1 W and 30 W.

Figure 4 Results of SNR by applying channel models with different transmitter powers and distances (see online version for colours)



The results show that whenever there is an increase in transmission distance, the SNR falls. This is mainly due to loss in transmission, which is considered as one of the most essential features of the SNR. With increasing distance, there is an accumulation of transmission losses and this creates a negative impact on SNR. Hence, in underwater WSNs, the transmission distance is inversely proportional to the SNR and this is true with different transmission powers. This confirms that the proposed channel model for estimating the SNR is valid for various transmission powers.

Also, the increase in transmitter power effectively increases the SNR value. This case is true as the distance of transmission is the same, the power of the transmitter from low to high SNR is 1–30 W. Since the source level power is considered to be a major factor due to SNR, the source level power may become high when the transmitter power is high. Hence, it could be concluded that the transmitted power is directly related with SNR, since the SNR value is consistent for all transmission distances and it finally confirms that the proposed model is applicable to various distances.

Table 1 Results of BER by applying channel models with different transmitter powers and distances

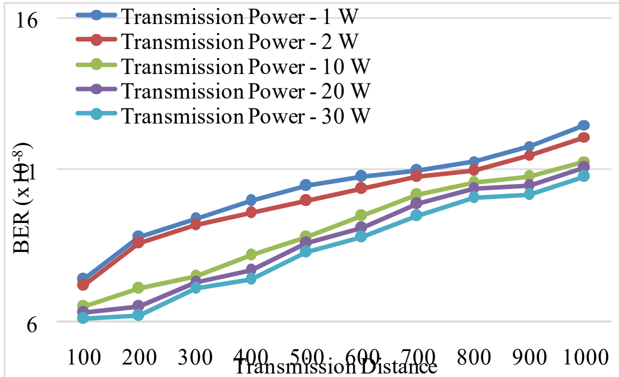
Distance	*Transmission power 1 W*	*Transmission power 2 W*	*Transmission power 10 W*	*Transmission power 20 W*	*Transmission power 30 W*
100	75	74	73	72	61
200	62	61	60	59	50
300	55	54	53	52	42
400	50	49	48	47	37
500	47	46	45	44	32
600	42	41	40	39	30
700	40	39	37	36	28
800	37	36	35	34	25
900	35	34	33	32	22
1,000	32	31	30	31	20

5.2 Evaluation of BER

The results of BER are shown in Figure 5, which plots the BER as a function of distance, which varies between 100 m and 1,000 m and the transmitter powers are set between 1 W and 30 W.

The results show that as transmission distance increases, the BER rises. This is due to loss in transmission, which is considered to be an essential feature of the SNR, which increases the BER. With increasing distance, there is an accumulation of transmission losses and this creates a negative impact on SNR, which leads to an increase in BER. Hence, in underwater WSNs, the transmission distance is inversely proportional to the SNR and this is true with different transmission powers. This confirms that the proposed channel model for estimating the BER is valid for various transmission powers.

Figure 5 Results of BER by applying channel models with different transmitter powers (x10^{-8}) and distances (see online version for colours)



Additionally, the increase in transmitter power effectively increases the SNR value, with falling BER. This case is true as the distance of transmission is the same; the power of the transmitter from high to low BER is 1–30 W. This is clarified based on the relationship between the BER and SNR. From Figure 4, it is concluded that as the power of transmission is high, SNR increases and hence BER is reduced. Consequently, the power of transmission is inversely proportional to BER. Since the source level power is considered to be a major factor due to BER, the source level power may become low when the transmitter power is high. Hence, it could be concluded that the transmitted power is directly related with BER, since the BER value is consistent for all transmission distances and this finally confirms that the proposed model is applicable for various distances.

Table 2 Results of BER by applying channel models with different transmitter powers (x10^{-8}) and distances

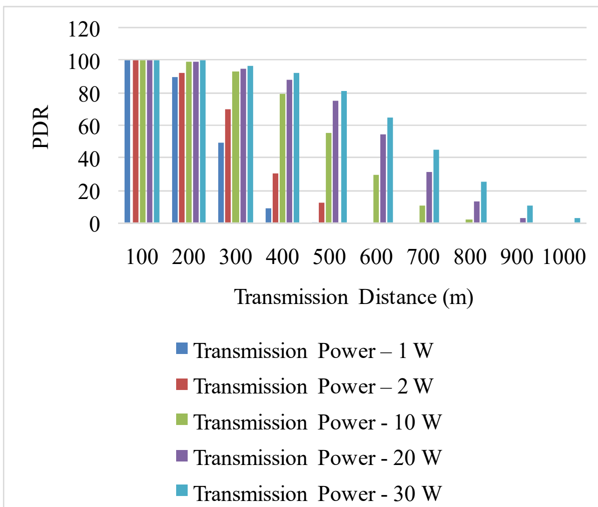
Distance	*Transmission power 1 W*	*Transmission power 2 W*	*Transmission power 10 W*	*Transmission power 20 W*	*Transmission power 30 W*
100	7.4	7.2	6.5	6.3	6.1
200	8.8	8.6	7.1	6.5	6.2
300	9.4	9.2	7.5	7.3	7.1
400	10	9.6	8.2	7.7	7.4
500	10.5	10	8.8	8.6	8.3
600	10.8	10.4	9.5	9.1	8.8
700	11	10.8	10.2	9.9	9.5
800	11.3	11	10.6	10.4	10.1
900	11.8	11.5	10.8	10.5	10.2
1,000	12.5	12.1	11.3	11.1	10.8

Further, it could be seen that the transmission distance of 1 W and 2 W leads to higher BER than other transmission distances. However, this creates a computational burden, with more expensive implementations compared with the light weight implementation of other transmission distances.

5.3 Evaluation of PDR

The results of PDR is shown in Figure 6, which plots PDR as a function of distance and it varies between 100 m and 1,000 m with transmitter powers between 1 W and 30 W.

Figure 6 Results of PDR with different transmitter powers and distances (a) 1 W (b) 2 W (c) 10 W (d) 20 W (e) 30 W (see online version for colours)



It is clear from the figure that as the distance of transmission increases, the PDR is reduced. This is due to the fact that as the transmission distance increases, there is a reduction in SNR and an increase in BER. The increase in BER is due to increase in number of bits received and the BER tends to get altered with interference, noise, synchronisation errors and distortion. Also, if a whole packet has been transmitted, high BER leads to lower PDR. In short, as the distance of transmission increases, SNR falls with an increase in BER and hence PDR is reduces, which is true for all transmitter powers. As the transmission power increases, it could be seen that the PDR increases with higher SNR and lower BER, which ensures a low probability of misleading packets during transmission. This leads to higher delivery of packets towards the destination node. It is confirmed from the results that the proposed channel model is applicable for various transmission powers.

Table 3 Results of PDR with different transmitter powers and distances

Distance	*Transmission power* *1 W*	*Transmission power* *2 W*	*Transmission power* *10 W*	*Transmission power* *20 W*	*Transmission power* *30 W*
100	99.8	99.9	99.9	99.9	99.9
200	89.9	92.5	98.9	99.3	99.8
300	49	70	92.9	95	97
400	9	30	79	88	92
500	0.03	12	55	75	81
600	0	0	29	54	65
700	0	0	10	31	45
800	0	0	2	13	25
900	0	0	0	3	10
1,000	0	0	0	0	3

6 Discussion

In this section, we discuss how this work accelerates the pace of research on IoUT. In Section 2, we first introduced numerous potential IoUT applications that are attractive to researchers. Then, in Section 3, we pointed out that a number of challenges exist. The challenging issues are attractive to researchers as well. Because reliability is one of the major concerns of IoUT, we investigated the UWSN channel models to calculate the reliability for IoUT in Section 4. The channel models provide a systematic way to compute the reliability between a pair of sensor nodes over IoUT. In Section 5, we conducted simulations to validate each part of the channel models, and confirmed that the models are applicable to underwater environments. We expect that the efforts will add value to future research on IoUT.

This section provides a discussion on how this model is most suitable for underwater design with the IoUT communication protocol. Consider the DAG routing protocol, which is intended to forward the packets to the destination node with effective routing. This is done through the selection of the shortest path among all the routes to transmit the data. The proposed routing protocol provides high reliability of packets during transmission using shortest path estimation. This leads to effective delivery of packets to the destination node with higher link reliability. Hence, it could be concluded that the proposed routing model with the IoUT communication protocol provides valuable communication trends in underwater WSNs.

However, to the best of our knowledge, this is the first method to support the routing of packets in underwater WSNs with the IoUT communication protocol. Hence, the comparison with the previous method may not be suitable to test the reliability of the system. However, the reliability or PDR of the communication protocol demonstrates its performance over the IoUT structure with the channel model. The use of the channel model, which is applicable under the sea, has helped in discovering the routing pattern in a most economical way. This method helps to overcome the disadvantages of the existing method in terms of its practical challenges, applications and channel models.

7 Conclusions

This paper has provided a new class of IoUT models in underwater WSNs with the DAG routing protocol. The proposed routing protocol in underwater WSNs demonstrates that the channel model is practical and can be made applicable for varying transmitting powers and distances. Specifically, as the power of transmission is high, the SNR is high and BER is low, which turns out to be successful PDR. However, as the distance in SNR and PDR is reduced there in an increase in BER. The results confirm that the channel model designed is reasonable and will help future research to test the IoT model in various other underwater scenarios. Further, the routing protocol can be implemented in IoT-based system and the routing protocol can be implemented in WSN, cognitive wireless systems and LTE-based system.

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