A Quality of Service Aware Source Routing Based Protocol for Underwater Wireless Sensor Networks

Original Scientific Paper

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Abstract *– Underwater Wireless Sensor Networks (UWSNs) handle many underwater applications such as environment monitoring, surveillance and navigation. These applications generate varied types of traffic such as continuous bit rate, sporadic and different packet sizes, leading to additional QoS requirements that are traffic and application dependent. This paper presents the development of a Quality of Service Aware Source Routing (QASR) protocol. QASR discovers multiple paths from the sources to the sinks and selects the most QoS compatible route among them. QASR is distinctive because it incorporates multiple QoS parameters such as Signal to Noise Ratio (SNR), latency and residual energy. Depending on which of these parameters are chosen, QASR has three variants, namely, QASR-Latency (QASR-L), QASR-Residual Energy (QASR-RE) and QASR-Signal to Noise Ratio (QASR-SNR). The performance of QASR protocol is compared against traditional source routing protocols, with simulations showing a reduction of about 10% to 20% in latency and about 5% to 10% lesser energy consumption than source routing. QASR protocol exhibits comparable performance to classic source routing protocols while simultaneously adhering to the QoS requirements of the application. It is also worth noting that the performance profile of all the three variants of QASR do not have sudden and drastic variations, with the performance profiles showing consistent trend-lines.*

Keywords*: Underwater Wireless Sensor Network (UWSN), Underwater Acoustic Communication (UAC), source routing protocol, Quality of Service (QoS), application traffic, DESERT simulator*

1. INTRODUCTION

Underwater Wireless Sensor Networks (UWSNs) are wireless sensor networks deployed in an underwater environment. UWSNs are used extensively in ocean sampling networks, environmental monitoring, undersea exploration, disaster prevention, assisted navigation, distributed tactical surveillance and mine reconnaissance [1]. Depending on the application that USWNs are deployed for, there is a considerable variation in the type of traffic in application layer that they have to be modelled for. As shown in Fig. 1, the varied applications naturally imply that a UWSN generates different kinds of traffic.

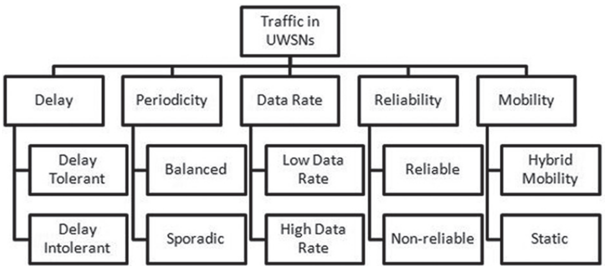

Fig. 1. Classification of traffic patterns in UWSNs

Application-based traffic patterns also demand an awareness of different Quality of Service (QoS) parameters. For example, pollution monitoring may require the system to support sporadic data generation while allowing for slightly relaxed reliability. In contrast, applications that sense underwater seismic activity have more stringent reliability requirements and generate continuous data. Furthermore, military applications that transmit live audio/video streams demand that the links support enhanced bandwidth requirements.

The authors of this paper envision the research presented here as a first step toward a more generic and versatile underwater communication architecture capable of addressing significant system performance parameters such as node mobility and deployment strategy, medium access, routing, modulation techniques, energy efficiency and QoS requirements. A recurring theme in MAC and routing protocols is that they are usually designed for specific application only. In addition, there is a distinct lack of research on unified communication architectures for UWSNs which can handle the communication requirements of different applications.

This paper presents a Quality of service Aware Source Routing (QASR) protocol that can be configured to choose QoS parameters on the fly. In particular, QASR protocol is designed to incorporate three QoS parameters: residual energy, latency and Signal to Noise Ratio (SNR). The principle of source routing is used to discover multiple routes from the source node to the sink node, and the most QoS appropriate route is chosen from among them. QASR protocol achieves energy efficiency by optimizing the route discovery process, caching reusable routes and applying reactive routing. In addition, QASR protocol is extensively simulated to ensure that it conforms to the requirements of various applications such as density of node deployment, traffic characteristics, energy efficiency and data packet size and frequency.

In the existing literature, QoS is viewed differently by different researchers. For example, in some research papers, the emphasis of QoS is mainly confined to traditional output parameters of the system such as throughput, latency, packet delivery and jitter. For UWSNs, another important QoS parameter of relevance is the energy efficiency. With the UWSNs increasingly catering to the more diverse and heterogeneous applications, the energy efficiency has moved from being a best-effort attempt to an essential parameter in taking decisions related to routing, clustering, medium access and even deployment strategies. Among others, the studies pertaining to energy efficient routing protocols are presented in [2] and [3].

In the recent past, void-aware and void mitigation routing has become a topic of considerable importance attracting significant interest from the researchers. Voids are black holes for data, resulting in overuse of the nodes in routing. This potentially causes a link outage because of the depletion of nodes in the network. The authors of [4] present the variants of void aware routing protocols and the associated challenges in their development.

The above referred research papers, and the literature reviewed in Section 2, clearly highlight an interesting shortcoming in the design of routing protocols for UWSNs. Designing a routing protocol for an acceptable single parameter of QoS, such as latency, energy efficiency, void avoidance or link quality, invariably results in an unresolved or unknown trade-off in other QoS parameters. Protocols are generally designed for specific traffic patterns, particular sensing environments and explicit QoS requirements. Therefore, it is a desirable and prudent wish that the needs of the varied applications of UWSNs and the traffic patterns they generate will be better served by a more generic and versatile routing protocol that supports multiple QoS parameters after its deployment also.

The primary emphasis of this paper is to address the following:

- Enhance the concept of source routing so that the source node is aware of all the available routes to reach the sink node.
- Use of this enhanced source routing and appropriate cross-layer information to track the QoS parameters as mandated by the developed routing protocol.
- Develop a source routing based protocol that can choose a path that supports the QoS requirements mandated by the application. For example, if the application changes the QoS parameter of interest, the protocol can handle that also.

The rest of the paper is structured as follows: Section 2 presents the related work, a brief description of some of the other QoS based routing protocols used in UWSNs. Section 3 describes the design of the QASR protocol, including the specifications and flowcharts used. Section 4 details the deployment scenario, subsequently covering the simulation results of QASR protocol and comparative analysis. Section 5 presents the conclusions arrived at in the paper. It also proposes some suggestions for future work in continuation of the research presented in this paper.

2. RELATED WORK

The review of literature presented in this section on the development of routing protocols for UWSNs looks at some research studies where specific QoS parameters such as link quality, traffic priority, reliability and channel awareness are considered.

In their study in [5], the authors enhance the Directional Flooding based Routing (DFR) and develop two variants that focus on end-to-end reliability as the QoS requirement. The two variants, namely, QoS-Aware DFR with Angle Adaption (QA_DFR_AA) and QoS-Aware

DFR with Threshold Adaption (QA_DFR_TA), are designed to adapt to node mobility, resulting in dynamic QoS requirements. The original DFR protocol does not accommodate mobile sources and sinks.

These protocols function by tracking the delivery ratio of each data flow and transmitting this information to the source and intermediate nodes of this flow. Since the sources are aware of link reliability using this information, further routing can be calibrated accordingly. Although this dynamic recalibration comes at the cost of increased overhead, there is an improvement in the delivery of packets, thereby satisfying the QoS requirement of reliability.

The authors in [6] propose a Channel Aware Routing Protocol (CARP) that considers the link quality as the QoS parameter of interest. Cross-layer principles are invoked to apply link quality to choose the next hop along the path to the sink. CARP also uses ready information, such as hop count, to route around voids while simultaneously focusing on nodes' residual energy and transmission power control to choose routes. CARP is analyzed by both simulations using Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing (SUNSET) [7] and real-life sea trials in the Mediterranean Sea. CARP is compared with a focused routing-based protocol, Focused Beam Routing (FBR) [8] and a flooding based protocol, EFlood. CARP is found to be at least 40% more energy efficient than FBR and EFlood. It has a significantly higher packet delivery ratio.

In [9], a QoS aware evolutionary routing protocol for underwater wireless sensor networks called QERP is presented. QERP is a greedy clustering-based routing protocol that increases packet delivery, reduces energy consumption, and decreases end to end delay. QERP protocol is based on the assumptions about location awareness, CSMA for medium access, power control and mobility patterns. QERP is designed to be evolutionary in nature, performing crossovers and mutations. A fitness function that considers the clustering cost and link quality cost is derived to perform route selection.

QERP is simulated using MATLAB, and its performance is compared with Depth Based Routing (DBR) protocol [10] and Vector Based Forwarding (VBF) [11] protocol. The delay was the least with QERP followed by DBR and VBF exhibiting the maximum delay. The clusters in QERP are smaller than other protocols that use the same concept, resulting in a better profile of energy consumption. The authors conclude that QERP improves the delay and reliability of data transfer in real-time scenarios.

QoSRP, proposed in [12], is a cross-layer QoS channel-aware routing protocol for the Internet of underwater acoustic sensor networks. This protocol is designed for cross-layer, QoS aware, multichannel routing to address time-critical marine monitoring applications. In addition, there are three mechanisms incorporated in it to aid data gathering to find vacant channels that can support high data rates while simultaneously avoiding congestion and balancing traffic.

QoSRP is simulated using NS-2 and AquaSim 2.0. Its performance is compared against Link quality-aware queue-based spectral clustering Routing Protocol (LRP) for underwater acoustic sensor networks [13], QERP and an energy efficient Multi-objective Evolutionary Routing Protocol (MERP) for reliable data gathering in the Internet of underwater acoustic sensor networks proposed in [14]. QoSRP performs better than the other protocols in conventional output parameters such as throughput, error rate, packet delivery and load balancing.

The research in [15] proposes a priority-based routing algorithm for underwater wireless sensor networks. This algorithm improves the QoS by classifying the traffic as high and low priority based on the delay tolerance. The network area is divided into logical cubes by network barriers. Low priority data is allowed to use only one side of the cube in its attempt to reach the sink, while high priority data uses all the sides of a cube. The nearest neighbor is chosen based on the Euclidian distance.

The performance of this protocol is compared with Geographic and opportunistic routing protocol with depth adjustment for mobile underwater sensor networks (GEDAR) protocol [16] using the OPNET network simulator. The simulations show that the high priority and low priority modes of both the protocols consistently perform better than GEDAR with respect to packet loss, latency, and residual energy.

A Delay-Intolerant Energy-Efficient Routing protocol with sink mobility in underwater wireless sensor networks, DIEER, is presented in [17]. This protocol assures data dissemination, even at the cost of energy efficiency. The study uses a multi-prong optimization approach to optimize sink mobility, data transmission and dissemination. This is applied to 3D mobile sensor networks characterized by dense deployment and mobile sinks. The authors claim that usage of a mobile sink reduces delay and energy consumption. Further, a mobile sink allows the optimization of transmission distance to reduce the number of retransmissions of data.

The DIEER protocol aims to maximize network lifetime and minimize end to end delay. Performance comparison is carried out with Mobicast [18]. The simulation results show that DIEER protocol performs better than Mobicast for dense deployments and achieves lower delays.

A summary of the literature reviewed is tabulated in Table 1. This summary highlights the QoS parameters considered, basic operation and limitations of the protocols reviewed and referred in this paper.

Table 1. Summary of Literature Reviewed

Sl. No.	Name of Protocol	QoS parameter/s	Basic Principles	Limitations of Protocol
1	QoS Aware DFR [5]	Node mobility and link reliability	Enhancement of DFR that allows node mobility. Routes are established using links that have been proved reliable previously.	Increased overhead possibly resulting in higher latency.
2	Channel Aware Routing Protocol [6]	Link quality	Link quality is used to choose the next hop along the path to the sink.	Effect of node mobility on protocol performance is not evaluated.
3	QoS aware evolutionary routing protocol [9]	Clustering cost and link quality cost	A greedy approach is applied that increases packet delivery, reduces energy consumption, and decreases end to end delay.	There is an assumption that the protocol is aware of the locations of the nodes and their mobility patterns.
4	Cross-layer QoS channel-aware routing protocol [11]	Time-critical communication	Protocol uses channel detection, assignment and forwarding mechanisms to find vacant channels that can support high data rates while avoiding congestion and balancing traffic.	Effect on node mobility on protocol performance is not evaluated.
5	Priority-based routing algorithm [15]	Traffic classification based on Priority	Network area is divided into cubes and paths are assigned based on priority of data.	Only two levels of priority may not be appropriate for real world scenarios.
6	QASR (Proposed in this Paper)	Signal to Noise Ratio, Residual Energy and Latency	Concept of source routing is used to select routes based on the QoS parameter chosen.	The route discovery can be enhanced to directly choose the QoS compliant route instead of selecting one from multiple possibilities.

3. DESIGN OF QASR PROTOCOL

The operation of the QASR protocol proposed in this paper is divided into three phases:

Phase 1: Selection of data haul node and data aggregation

Phase 2: Route establishment

Phase 3: Data transfer

These phases are detailed in this section after the introduction of network architecture for QASR.

3.1. NETWORK ARCHITECTURE

To facilitate the implementation of QASR, it is assumed that the nodes of UWSN are deployed in clusters in a stretch of ocean. The nodes are classified as sensing nodes, data haul nodes and sinks. Sensing nodes are static nodes responsible for sensing information and broadcasting it to the data haul nodes. The data haul nodes are mobile nodes, analogous to cluster heads, capable of movement and control of two aspects of the communication: They receive data from the sensing nodes in their cluster. This is done by moving within the cluster. The data haul nodes also create a multi-hop ad-hoc network among themselves, sending data collected from their clusters towards the sink. A single cluster is shown in Fig. 2, and a representation of the deployment of sensor nodes is depicted in Fig. 3.

Sensing and data-haul nodes are functionally interchangeable; the sensing node with the highest residual energy is chosen as the data haul node for a particular data flow. The protocol dictates that the data haul nodes be mobile while the sensing nodes are static. There are multiple sinks in the network architecture, and transmission is deemed successful if the data reaches any one of the sinks.

The following are the assumptions to facilitate the protocol design:

Assumption 1: The sensing nodes are aware of their positions in the Cartesian coordinate system.

Assumption 2: The sensing nodes of each cluster are fixed; by extension, the coverage area of each cluster is fixed.

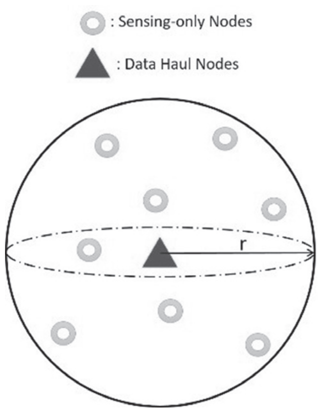

Fig. 2. A single cluster consisting of sensing nodes and one data haul node

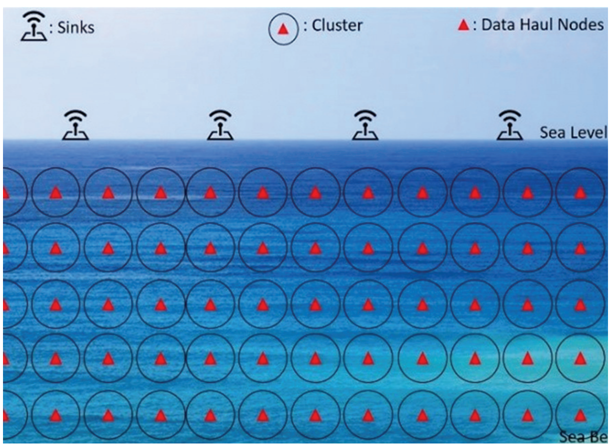

Fig. 3. Typical deployment scenario

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3.2. SELECTION OF DATA HAUL NODE AND DATA AGGREGATION

One of the main assumptions of QASR protocol is that the area of interest covered by each cluster is fixed along with the members of the cluster. Each cluster can be viewed as an undirected, fully connected graph G (V,E) where $V \in$ set of nodes in that cluster and E represents the links. The weight of each link is calculated as the Euclidian distance between the pair of nodes it connects. For example, if S_i and S_j are two sensing nodes with coordinates S_i (x_i, y_i, z_i) and S_j (x_j, y_j, z_j), then the weight of the edge between them is given by Equation (1).

$$E_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2} \qquad (1)$$

The graph model of the cluster is illustrated in Fig. 4. This is a cluster with five sensing nodes, and each node is connected to each other.

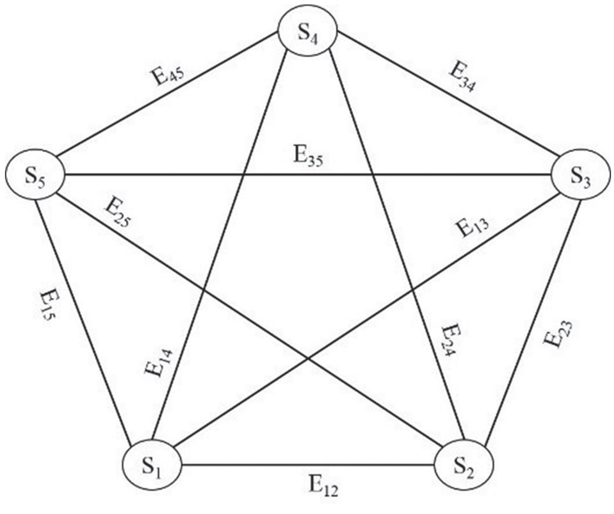

Fig. 4. A fully connected cluster showing the edges between the sensing nodes

The data haul node for each cluster is chosen as the node with the highest residual energy. The data haul aggregates the data by visiting each of the sensor nodes. Since one of the sensing nodes is designated as the data haul node, QASR protocol calculates the shortest path of all-pairs for the graph so that each node is aware of the shortest path to be taken to reach all the nodes.

The all-pairs shortest path involves finding the shortest path from all possible sources to destinations within the cluster. Since this is an undirected graph with no negative weights, the solution can be computed using Dijkstra's algorithm or the Floyd-Warshall algorithm. However, since Dijkstra's algorithm has a higher time complexity (($ElogV$)) than the Floyd-Warshall algorithm ($O(V^3)$), the latter is chosen to find the all-pairs shortest path.

Floyd-Warshall algorithm uses dynamic programming to check if a given path from vertex S_i to S_j has a lower total weight alternative if the path goes through another vertex S_k, i.e., $S_i \rightarrow S_k \rightarrow S_j$ is a lower weight alternative to $S_i \rightarrow S_j$. The mathematical formulation of the Floyd-Warshall algorithm is given in Equation (2).

$$\mathrm{A[N]} \leftarrow D_{S_i,S_j} = \begin{cases} 0 & if\ S_i = S_j \\ E(S_i, S_j) & if\ S_i\ and\ S_j\ are\ connected \\ \infty & if\ S_i\ and\ S_j\ are\ not\ connected \end{cases} \qquad (2)$$

In Equation (2), A[N] refers to the cost matrix with N nodes, $D_{Si\,Sj}$ indicates the total distance between nodes S_i and S_j and $E(S_i, S_j)$ is the edge between the nodes S_i and S_j.

This paper uses the Floyd-Warshall algorithm to create the array of routes R[N]. The algorithm is detailed in Algorithm 1 as shown below:

Algorithm 1 Floyd-Warshall Algorithm

Require: All pair shortest paths $P[N]$
Ensure: Cost Matrix $A[N]$

$R[N] \leftarrow$ path (S_i, S_j)=0 $\quad \forall\ S_i, S_j \in N$
do k=1,N
  do i=1,N
    do j=1,N
      if $D(S_i, S_k)$+$D\_(S_k, S_j)$<$D(S_i, S_j)$
      then$D(S_i, S_j)$= $D(S_i, S_k)$+$D(S_k, S_j)$
        if *path* (S_i, S_k)=0
        then *path* (S_i, S_j)←k
        else *path* (S_i, S_j)← *path* (S_j, S_k)
        end if
      end if
    end do
  end do
end do
do i=1, N
  do j=1,N
    if *path* (S_i, S_j)=0 **then** *path* (S_i, S_j)←j
    end if
  end do
end do

This algorithm ensures that all the nodes have the cost matrix and know the shortest path to reach all the other nodes. This information is helpful once a node is designated as the data haul node.

To identify the data haul node, QASR protocol performs an intra-cluster MAC-level broadcast of the residual energy of each node in the cluster. Every node in the cluster broadcasts a *ResEn* frame that consists of its node ID and residual energy. This *ResEn* frame is stored by each node that receives it and subsequently forwarded to the other sensing nodes in the cluster. Each node continues to receive this frame from other nodes until they have the residual energy of all the nodes in the cluster.

The node with the highest residual energy is chosen as the data haul node. Mobility patterns are set up so that the data haul node moves to the vicinity of each sensing node according to the cost matrix derived. The cost matrix does not change based on energy or any other parameter, and it continues to be applied as a shortest path finder.

At the end of phase 1, the UWSN is ready to discover routes to the sink and use them according to the application requirements. Additionally, data haul nodes are identified, and mobility patterns have also been set up.

3.3. ROUTE ESTABLISHMENT

Route establishment in wireless networks can be primarily of two types. In reactive routing, a route is established between node A and node B only when there is data to be transmitted from node A to B. Conversely, proactive routing involves all the nodes in discovering a route to all other nodes at the initial start of the network irrespective of whether they will be needed. QASR protocol performs reactive routing by considering the mobile data haul nodes as a multi-hop ad-hoc network. This reactive routing is based on the Source routing for Underwater Networks (SUN) protocol [19].

A route request (RREQ) packet is broadcast from the source data haul node with the destination as the broadcast address of the sinks. This RREQ packet is forwarded by the intermediate data haul nodes till the RREQ reaches one of the sinks. Every intermediate node that forwards the route discovery packet adds its address to the header. When the sink receives the RREQ, it completely knows the entire path followed. The sink, as a destination, unicasts a route reply packet (RREP) along the same path to the source data haul node. Since the RREQ is broadcasted, the source receives multiple RREPs and can choose the 'best' route to transmit the data. If an intermediate node does not receive an acknowledgement for forwarding the data to the next hop, it initiates a route error (RERR) packet and transmits it towards the source so that all the intermediate hops can update their routing tables. Routes that are used successfully are cached so that they can be reused.

The QASR protocol proposed in this paper consists of two types of packets: Control packets and data packets. Control packets are used for route discovery and maintenance, while data packets are used for aggregated data at data haul nodes. The control packet format is shown in Fig. 5.

Packet Type	Mode	Mode Value	Source Address	Packet ID	Destination Address	Path

Fig. 5. Control packet format of QASR

In Fig. 5, Packet Type indicates whether the packet is RREQ, RREP or RERR. If the packet is an RREQ, the destination address is the broadcast group address of sinks, while the RREP uses the destination address field in unicast mode. The Path field is implemented as a structure to store a list of the nodes visited during route discovery.

QASR protocol achieves QoS awareness by working in three modes: SNR, residual energy and latency. In the SNR and residual energy modes, the mode value field stores the minimum SNR or residual energy encountered during propagation of RREQ. The same information is unicast back to the source in the RREP packet, enabling the source to choose the path based on the QoS requirement of the application. The latency mode is similar, but it tracks the cumulative latency in the entire path instead of hop to hop. This control packet structure enables the source data haul node to choose a path with minimum SNR, residual energy or end-to-end delay. The caching of routes allows them to be reused without going through route discovery overhead.

Cross Layer Interactions

For QASR protocol to achieve the different modes of operation and to identify the data haul node itself, a significant amount of information is used that is not conventionally available at the network layer. For example, the requirements of the application based on which the routes are chosen are available at the application layer. The process of computing the minimum SNR and residual energy requires information typically available at the Physical layer. QASR protocol works on the principle of cross-layer optimization, assimilating all this information at the network layer and taking routing decisions based on them. Fig. 6 depicts the exchange of information in the QASR protocol.

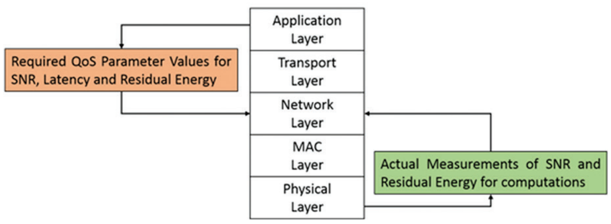

Fig. 6. Cross layer interactions of QASR

Route Discovery

RREQ packets are used if the cache does not have a route from source to destination, or a RERR is encountered. The flowchart for the generation of RREQ is shown in Fig. 7, and its propagation at the intermediate nodes is shown in Fig. 8.

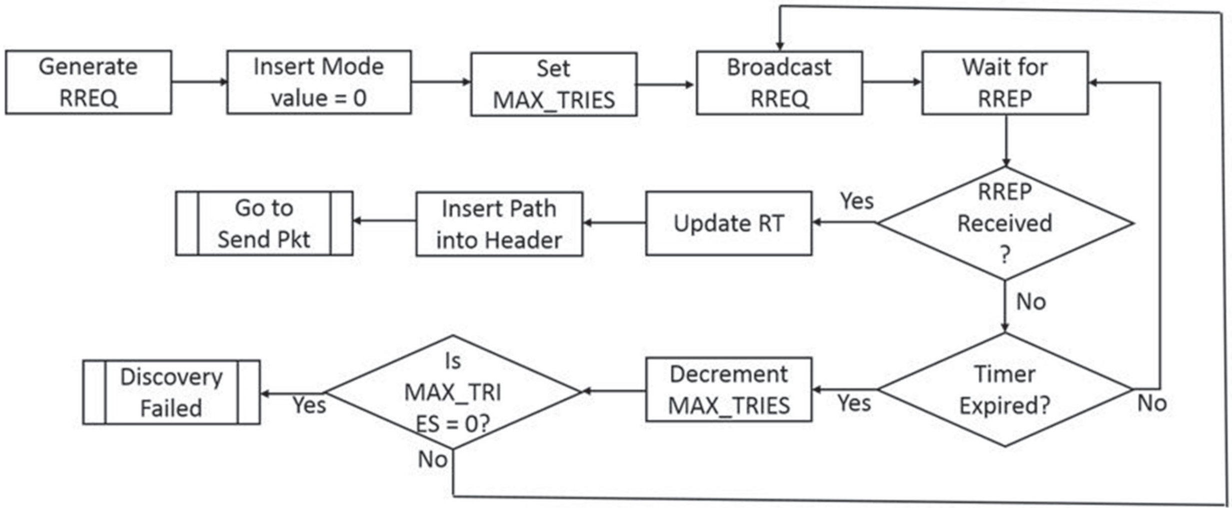

Fig. 7. Generation of RREQ

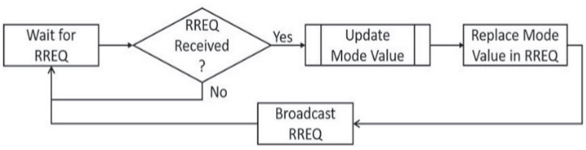

Fig. 8. Propagation of RREQ

When the RREQ is generated initially, the mode value is set to zero. When an intermediate node receives an RREQ, it extracts the mode value from it. Then the intermediate node calculates the SNR of the incoming packet or the residual energy of itself from the physical layer. If the calculated SNR/residual energy is lesser than the mode value in the packet, the intermediate node updates the mode value. This ensures that the mode value indicates the minimum SNR or residual energy at every hop until that point in the propagation. The intermediate node also updates the timestamp field in RREQ to reflect the time of receipt of the packet. Once the RREQ reaches the sink, mode values and timestamp information are transmitted back to the source data haul node. The algorithm for updating the mode value is shown below.

Algorithm 2 Mode Value Update

Require: Updated mode value in RREQ
Ensure: Existing mode information $RREQ.mode$, Existing mode value $RREQ.modeval$, Existing time $RREQ.time$, timestamp $time$, Signal to Noise Ratio SNR and residual energy RE

do while $RREQ.received$ is **TRUE**
  if $RREQ.mode = SNR$ **then**
    if $RREQ.modeval > PHY.SNR$ **then** $RREQ.modeval = PHY.SNR$
    end if
  if $RREQ.mode = RE$ **then**
    if $RREQ.modeval > PHY.RE$ **then** $RREQ.modeval = PHY.RE$
    end if
  $RREQ.time = time$
end do

Route Reply

The transmitted RREQs reach the destination with information about minimum SNR or residual energy and the end-to-end delay in the route that was taken. The destination copies these values into the RREP packet and unicasts it using the path information already present to transmit this to the source. The algorithm for the generation and propagation of RREP is presented in Fig. 9.

After the route establishment phase, QASR protocol is aware of all possible routes from source to destination. The data is aggregated at the data haul nodes, ready for transmission towards the sink.

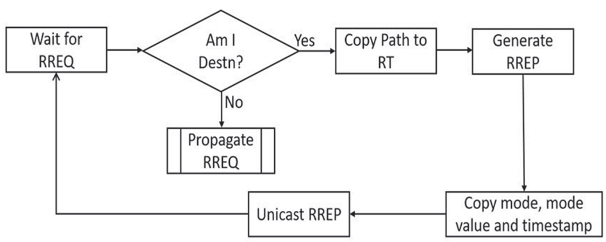

Fig. 9. Generation and propagation of RREP

Once the route establishment is completed, the source must choose the best route among the available options. This is carried out by considering the application requirements of either SNR, latency or residual energy. Depending on the required mode of operation, QASR protocol initializes the respective path and inserts it into the data packet header.

The packet is subsequently transmitted to the next hop. The functioning of QASR protocol at the source data haul node is illustrated in Fig. 10.

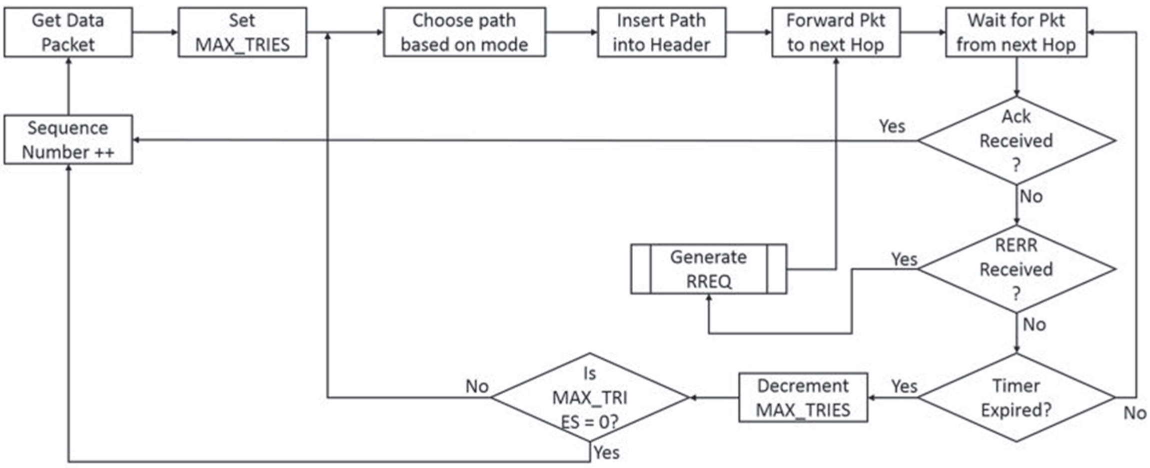

Fig. 10. QASR at source data haul node

4. SIMULATION ANALYSIS

To simulate QASR protocol, the DESERT Underwater Framework is used, which is an NS-2 based framework equipped with extensions to facilitate cross layer communication and multiple radio interfaces and underwater acoustics. The performance of QASR protocol is compared with Source routing for Underwater Networks (SUN) [19] and Information Carrying based Routing Protocol (ICRP) [20]. The performance of these protocols is evaluated in terms of their Packet Delivery Ratio (PDR), latency and energy consumption. The variable parameters are node mobility, node density and data rate. Subsequently, an analysis of the energy consumption is presented with respect to the improvement noticed in the energy efficiency of the QASR protocol.

4.1. DETAILS OF SCENARIO FOR SIMULATION STUDIES

The coverage area is 3000m3. Every cluster is assumed to have ten sensing nodes. A multi-sink architecture is considered, with 30 nodes acting as sinks. Where used, the mobility model will be random waypoint. The simulation parameters are listed in Table 2.

Table 2. Simulation parameters

Parameter	Default	Minimum	Maximum
Coverage Area (m)	3000*3000*3000		
Data Haul Nodes	20	5	50
Traffic (kbps)	25	10	100
Mobility (ms-1)	Static	0.3	3
Mobility	Based on the data aggregation algorithm		
MAC Protocol	Carrier Sense Multiple Access		

4.2. PERFORMANCE WITH VARIABLE MOBILITY

In this set of simulations, the mobility of the nodes is varied. The performance graphs of the different routing protocols in terms of PDR, latency and energy consumption are presented in Fig. 11 to Fig. 13 respectively. Even though QASR protocol has been designed for mobility, the performance is relatively poor when the mobility is low. This means that the data haul nodes cannot reach all the sensing nodes in time to aggregate the information, leading to reduced performance initially. Once data haul nodes are fast enough to reach the sensors, there is a significant improvement in the performance of QASR protocol. The fundamental behavior of the QASR protocol is the same irrespective of whether it is operating in the QASR-L, QASR-RE or QASR-SNR mode. The only difference is in the value carried in the mode field. Hence, it is noted that there is not much variation in the performance of the three variants of QASR.

The results of Fig. 11 show that although SUN has a higher packet delivery ratio than the variants of QASR protocol for static nodes, as mobility increases, PDR of QASR is about 10% higher than SUN. The variation of latency with change in mobility is shown in Fig. 12. ICRP has a higher latency (about 10% to 15%) with increased mobility, while the other protocols show comparable performance.

Fig. 13 shows the energy consumption of the protocols being compared. Since SUN and ICRP are not designed for mobile data haul nodes, their energy consumption is higher for static nodes. This is attributed to the fact that the network does not converge completely when the data haul nodes are static. On the other hand, variants of QASR protocol show a predictable linear increase in the energy consumed by the nodes as the mobility of nodes increases.

crease in energy consumption of all the protocols. The increase in node density affects all the protocols in a similar fashion.

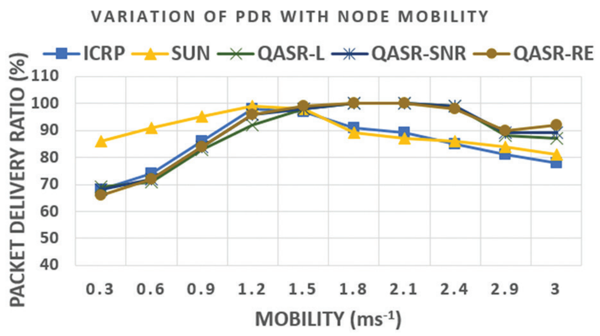

Fig. 11. Variation of PDR with mobility

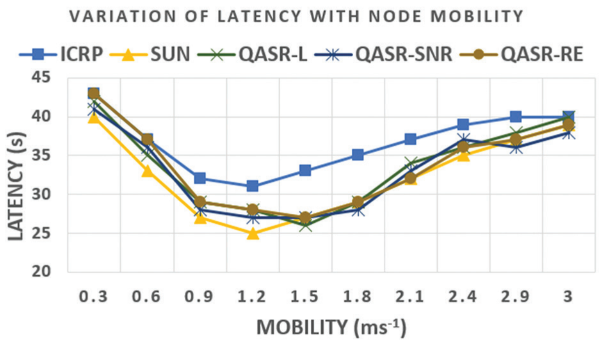

Fig. 12. Variation of latency with mobility

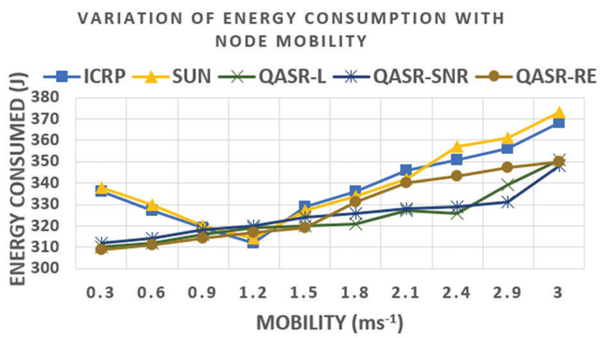

Fig. 13. Variation of energy consumption with mobility

4.3. PERFORMANCE WITH VARIABLE NODE DENSITY

This set of results is obtained by varying the density of the nodes by changing the number of clusters. For the coverage area size considered, the number of clusters is increased from 5 to 100, with each cluster containing one data haul node. Fig. 14 shows that as the number of clusters increases, the PDR of SUN and ICRP reduces drastically. In addition, there is a reduction of about 25% in the number of packets delivered. Since the data haul nodes of QASR protocol are mobile, they can accommodate larger clusters, thereby reducing overheads and increasing PDR. The results shown in Fig. 15 exhibit a similar trend, with the latency of SUN and ICRP about 150% to 200% more than QASR protocol. This increase is attributable to the increase in the overhead communication in the network because of increasing clusters. Fig. 16 shows a fairly linear in-

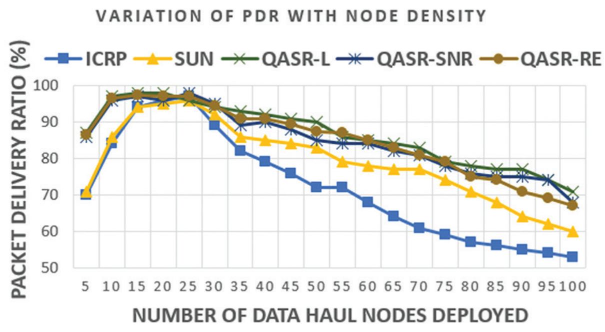

Fig. 14. Variation of PDR with node density

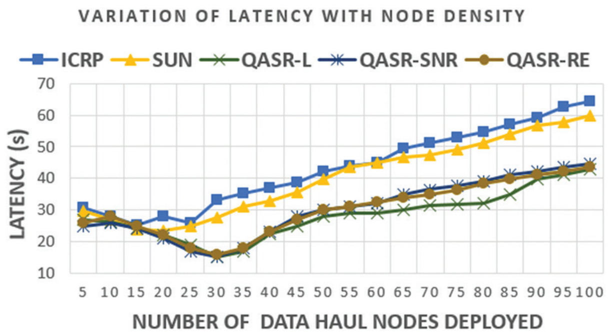

Fig. 15. Variation of latency with node density

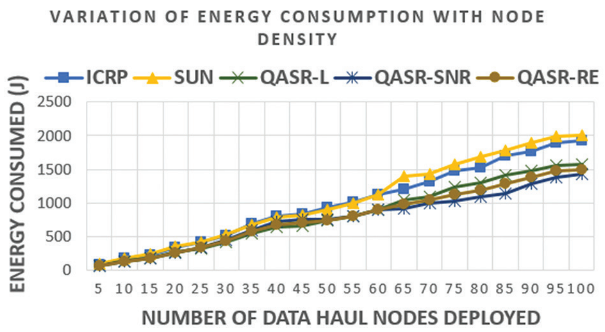

Fig. 16. Variation of energy consumption with node density

4.4. PERFORMANCE WITH VARIABLE DATA RATE

In this set of simulations, the data rate of the traffic is changed. The performance graphs of the different routing protocols in terms of PDR, latency and energy consumption are presented in Fig. 17 to Fig. 19 respectively.

Fig. 17 illustrates the deterioration of PDR with increasing data rate. While all the protocols show a comparable decline, SUN and ICRP perform comparatively worse for extremely high data rates of 90 kbps to 100 kbps. This is because of the increasingly frequent route discovery and maintenance carried out by SUN and ICRP when the data rate increases. QASR protocols shows a similar trend since it is also based on reactive routing, with the routing overhead increasing with data rate.

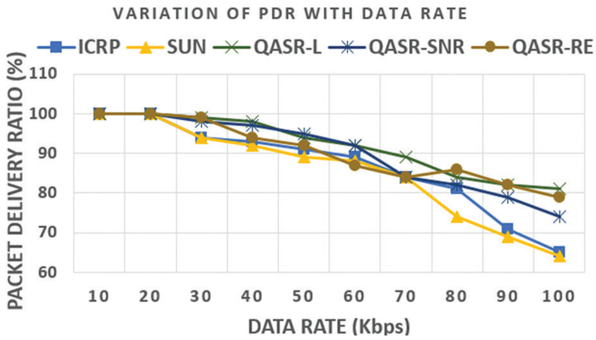

Fig. 17. Variation of PDR with data rate

Fig. 18 shows the effect of increasing data rate on the latency of the routing protocols. It is noted here that as the data rate increases, the latency also shows a corresponding increase of about 20%, with ICRP showing the maximum latency among the protocols. The latency values of QASR protocol are comparable to the other protocols. Fig. 19 shows the energy consumption, which is by and large linear. In comparison with QASR protocol, SUN and ICRP show an increase of about 10% to 40% of the energy consumed, with an increasing data rate.

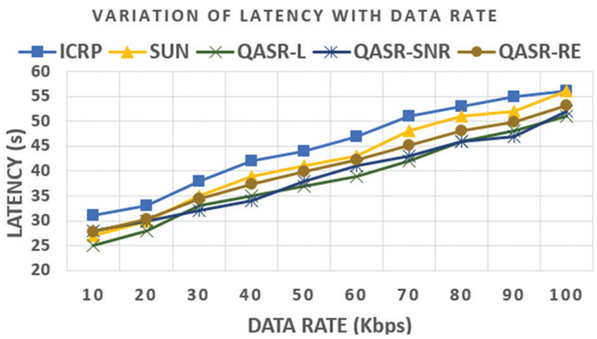

Fig. 18. Variation of latency with data rate

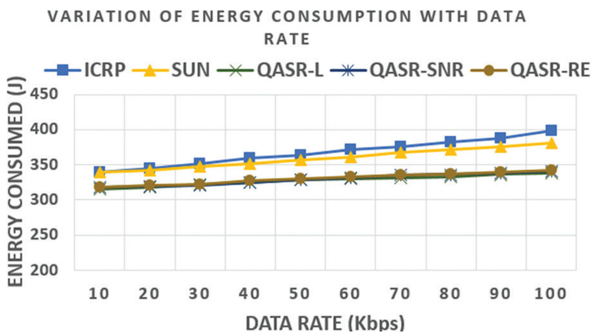

Fig. 19. Variation of energy consumption with data rate

5. CONCLUSION AND FUTURE DIRECTIONS

This paper presents the development and simulation analysis of QASR protocol, a QoS aware source routing protocol for UWSNs. QASR can choose the best routes based on QoS requirements of SNR, latency or residual energy. Depending upon the parameters based on which the routes are chosen, QASR protocol works in QASR-L, QASR-RE or QASR-SNR modes of operation. The intra-cluster data aggregation is handled by the sensing nodes' broadcasting information when the data haul node visits them. Inter-cluster communication is achieved by building an ad-hoc multi-hop network to reach the sinks.

QASR protocol is developed to be QoS aware, choosing different QoS parameters. For example, it can select between latency, residual energy and SNR. Such a provision for the choice in the selection of QoS parameters allows QASR protocol to be reconfigured while executing to consider any one of these parameters. This is a significant improvement over other QoS-based protocols optimized for one QoS parameter only.

QASR performs particularly well pertaining to latency, showing a reduction of about 10% to 20% for varying mobility and data rate. For increasing node density, the performance of SUN and ICRP deteriorate drastically by a factor of 150% to 200% compared to QASR protocol. The energy consumption of QASR protocol also deteriorates gradually, without any sudden drops and sharp variations. In some cases of increasing node density and data rate, the energy consumption of QASR protocol is about 5% to 10% lesser than SUN and ICRP. It is observed that QASR protocol exhibits performance comparable to source routing in underwater networks while simultaneously ensuring that the QoS requirements of the application are met.

The performance of the QASR protocol shows that it works fairly reliably for scenarios with varying mobility, node density and data rate. The results show that the protocol performs gracefully, without any kinks, sudden drops or unexpected behavior. Based on the various simulation studies presented in this paper, it is reasonable to infer and conclude that the QASR protocol has performed well within the generally expected and acceptable trends of performance metrics. This in turn lends QASR protocol a desirable attribute of reliability. The performance characteristics of QASR protocol are adequate to accommodate different types of traffic patterns and other application specific requirements.

It is typically observed that while designing energy efficient communication architectures for UWSNs, other QoS parameters are relegated to lesser importance. This is a valid decision since energy efficiency becomes an overarching design requirement. Therefore, the authors propose to use QASR protocol as a building block of a more generic and versatile underwater communication architecture that can be applied to scenarios requiring QoS and energy efficiency.

One of the proposed enhancements to the QASR protocol is to further optimize the process of route discovery. Currently the QASR protocol chooses the route that conforms to the QoS requirement specified during route discovery. This step involves looking at all the routes discovered and then selecting the best option among them. The authors propose to enhance route discovery such that the non-QoS compatible routes can be eliminated in this phase. This will subsequently ensure that the best route that satisfies the required QoS parameter is discovered in a straightforward manner.

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