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A Survey on Routing Protocols for Underwater Wireless Sensor Networks

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ABSTRACT

Underwater Wireless Sensor Networks (UWSNs) has gained an increasing interest in the past few years from the research community. The harsh underwater environment makes it challenging to design and implement protocols especially tailored for UWSNs. While some of the already proposed solutions for UWSNs may be reused, the unique characteristics of the underwater environment usually necessitate dedicated solutions. Several routing protocols with various goals have been proposed in the literature. In this paper, we introduce several routing protocols and classify them according to the main purpose they were developed for. Indeed, in the early days of UWSNs deployment, the main objective of routing protocols was only limited to guaranteeing the successful delivery of a data packet to a final destination. Then, once UWSNs have been well settled down, researchers rather focus on designing energy efficient routing protocols as sensors' battery power is the most precious and scarce resource that highly impact the network lifetime. In this survey, we provide a detailed overview of: Reliable Data Delivery Routing Protocols and Energy Efficient Routing Protocols.

KEYWORDS: ***Routing, Underwater, Energy, Data Delivery***

I. INTRODUCTION

In the past decade an increasing research interest have been devoted towards exploring oceans and seas since they cover the majority of the earth. Therefore, Underwater Wireless Sensor Networks (UWSNs) was developed. UWSNs have several useful applications such as offshore exploration, tsunami warnings, oil field exploration, control of mineral extraction and studying the wildlife of the underwater environment.

An UWSN consists of three main components: i) sensor nodes that are deployed underwater with different locations and depths ii) floating sinks that receive data generated from the sensor nodes iii) an offshore sink that receives data from the floating sinks and process them. The communication between sensor nodes and the floating sink is through acoustic waves while the communication between the floating sink and the offshore sink uses radio signals.

The underwater environment is known for its harsh characteristics and their effect on the acoustic communication among sensor nodes. For instance, a data packet travelling from one node to another is prone to high attenuation, limited bandwidth, high bit error rate, potential path loss and noise. Moreover, the network has a limited lifetime since sensor nodes have limited energy budget and are impossible to recharge. Indeed, the power needed for acoustic underwater communications is much greater than in terrestrial radio communications. The reasons behind this can be summarized as follows. First, underwater communication is subject to transmission over higher distances. Second, to enable underwater communication, more complex signal processing techniques are needed at the receivers to counterbalance the impairments of the channel. Finally, the harsh characteristics of the acoustic channel are time and space dependents which make the situation even worse.

For these reasons, researchers are always proposing new solutions to overcome the effects of the previously mentioned challenges and limitations. In this paper, we will rather focus on routing protocols and we rather focus on the most significant ones. Routing protocols will be classified into two types: i) Reliable Data Delivery and ii) Efficient Energy Consumption. The first category focuses on routing protocols that aim at providing successful data delivery while the second category represents the routing protocols that target an efficient use of sensors battery powers to maximize the network lifetime.

II. UNDERWATER WIRELESS SENSOR NETWORKS ROUTING PROTOCOLS

In this section, we will present the two categories of UWSNs routing protocols and list the most important ones of each. The first category is Reliable Data Delivery Routing Protocols where protocols aim at successfully delivering data packets to a final destination. The second category is Energy Efficient Routing Protocols where protocols rather focus on maximizing the use of the limited energy budget and prevent overloading some sensor nodes more than others in UWSNs to extend the network lifetime.

A. Reliable Data Delivery Routing Protocols

Routing protocols in this class, as previously mentioned, have a main unique purpose of successfully and reliably delivering data packets to a final destination. This category can be further classified into Location-based Routing Protocols and Pressure-based Routing Protocols. The former assumes that each sensor node have location information of either itself, or possible next hops, or final destination or all of them. While the latter requires the nodes to know only their depth relative to the surface.

1- Location-Based Routing Protocols:

a) Focused Beam Routing (FBR)

Focused Beam Routing (FBR), as introduced in [1], is a dynamic energy efficient position-based routing protocol.

FBR assumes that nodes can be either static or mobile. Static nodes know their own location upon deployment and the mobile ones are equipped with an internal navigation system that enables location determination. Consequently, FBR assumes that every underwater sensor node knows its own location as well as the one of the final destination. However, the location of intermediate node is not required.

FBR operates at multiple transmission power levels that are set upon the deployment of the protocol. Clearly, every power level allows the source to reach a given set of intermediate nodes within a certain transmission radius forming a virtual cone. Having a data packet to be sent, a sender, say A, starts by sending a RTS packet with the lowest power level. The RTS packet contains the locations of the sender as well as the final destination, say D. Every intermediate node that receives the RTS packet, will calculate its current position relative to the line AD, as shown in Figure 1. If the intermediate node is within a cone of angle ($\pm\Theta/2$) from the transmitter towards the final destination then this node is considered as a potential next hop candidate and it will send a CTS packet. Note that if no CTS packet is received the power is increased one level at a time until a node is found. The data packet is then sent the forwarding nodes, also called relays. This process is repeated until the packet reaches the final destination.

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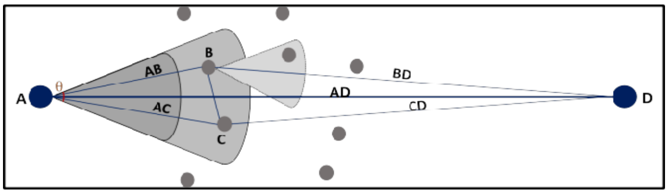

Figure 1: FBR Protocol

Even though FBR outperforms the pre-established routing protocols like the ones based on Dijkstra's algorithm, it still suffers from some performance issues [1]. For instance, the water movement may cause the network nodes to be sparse. Consequently, a forwarder may not succeed to find a relay within the transmission cone area even though there is some nodes outside the cone area that may act as a relay.

b) Vector-Based Forwarding (VBF)

Vector Based Forwarding (VBF) is another position- based routing protocol that was introduced in [2]. VBF tries to overcome the node mobility limitation, that may requires frequent routing maintenance, by imposing to each packet originating from the source to contain the location information of the source, previous forwarding nodes and the final destination. The main idea of VBF is that every sensor node that receives a data packet starts by forming a virtual pipe of a given radius, as shown in Figure 2, connecting the source to the final destination. If the receiving node is within the virtual pipe, it will continue forwarding the packet.

Therefore, a unique data packet will be forwarded along redundant paths which makes VBF reliable against packet loss.

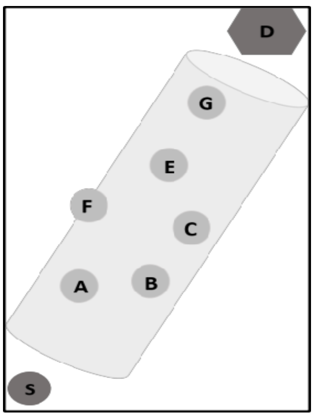

Figure 2: VBF Protocol

As it may be expected, the performance and robustness of VBF is very sensitive to the pipe radius as well as network density. Indeed, in sparser area, no node may be found in the pipe which will prevent the progress of the data packet. However, in other areas, the use of the virtual pipe concept may result in an overuse of some underwater nodes which can exhaust their battery power.

c) Hop-By-Hop Vector-Based Forwarding (HH-VBF)

Hop-By-Hop Vector Based Forwarding (HH-VBF) was introduced in [3] to overcome VBF's drawback by letting each forwarder node form its own pipe, shown in Figure 3, instead of the original approach where only one pipe connecting the source to the final destination. This way, forwarder nodes form better paths especially in sparse network where node densities are quite low.

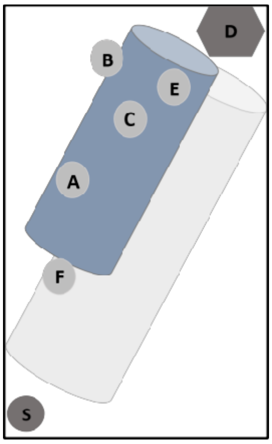

Figure 3: HH-VBF Routing Protocol

2- Pressure-Based Routing Protocols

a) Depth Based Routing (DBR)

Depth Based Routing (DBR) is the first pressure-based routing protocol [4]. Nodes in this protocol don't need to know their own complete location. Instead, only their depth relative to the surface is required. DBR is a dynamic routing protocol where routes are not pre-determined or fixed where the routing decision will be performed hop by hop.

DBR follows a multi-sink architecture where

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every packet sent from sensor nodes can be sent to any of the sinks on the surface which helps increasing the packet delivery ratio. The main idea of DBR is that when a source node sends the packet, it attaches its own depth information to the header of the packet. When a forwarder node receives the packet, it compares its own depth to the one included in the header. If it has a lower depth, i.e. closer to the surface, then it is a forwarder candidate otherwise the node discards the received packet. The process is repeated until the data packet is received by one of the sink nodes.

DBR suffers from a serious limitation called, the void region problem. It can be found in a sparse area of nodes, where it is possible to find no eligible node as a forwarder node. In other words a data packet could be received by an intermediate forwarder that has no neighbors with less depth than it has. Reaching this node, the packet won't be able to progress any more toward the sink even though a possible route through a higher depth node may be available. This is a limitation not solved in DBR and reduces its feasibility in sparse networks and thus it opens a research issue for other researchers.

b) Hydraulic Pressure-Based Any-Cast Routing (Hydrocast)

One more pressure-based routing protocol introduced in

[5] is Hydrocast. It is a hydraulic any cast routing protocol where it is similar to the previously mentioned pressure- based DBR in using pressure levels as a metric for choosing the forwarding set. The most important contribution of Hydrocast is the void region problem resolution. Hydrocast is divided into two main procedures; forwarding set selection and recovery mode.

Forwarding set selection is similar to the process of DBR where depth is used as metric to choose the forwarding set.

Accordingly, only nodes with less depth than the previous forwarder will be allowed to forward the packet. The second procedure is the recovery mode where it overcomes the void region limitation faced by DBR. Recall that the void region problem happen when a data packet reaches an underwater sensor node having no neighbor with less depth. This node is commonly referred to in literature as local maximum node. Hydrocast try to provide the local maximum nodes with a recovery path that goes through a higher depth neighbor in order to reach a node with less depth that the local maximum node. Consequently, after a several forwarding attempts, a local maximum node will succeed to build a recovery route.

Although Hydrocast focuses on providing a returning path to a stuck data packet, this process wastes a notable amount of the sensors energy and thus minizing the network lifetime.

c) Void-Aware Pressure Routing (VAPR)

Another pressure-based routing protocol, called Void- Aware Pressure Routing Protocol (VAPR) was introduced in [6]. The main contribution of VAPR especially compared to Hydrocast is preventing a packet from reaching a local maximum node instead of providing a recovery path for it.

To do so, VAPR goes into two phases; first, the enhanced beaconing and the opportunistic directional data forwarding. The former consists of periodically exchanging beacon messages that have to be initiated by the surface sink. The beacon message mainly includes four information: sender's depth, sender's hop count to the sink, sender's forwarding direction towards the surface sink and the sender's next hop data forwarding direction. Those beacon messages are originated by the surface sink and updated and forwarded by every receiving node. The hop count field reflects how far a node is from the surface node according to the best path. Indeed, upon the reception of multiple beacon message a node will consider only the information contained in the beacon message of the closet node to the sink.

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According to VAPR, there is two possible forwarding direction up or down. A given node forwarding direction is set to up if the beacon was received from a shallower node and is set to down if it was received from a deeper node. The next hop data forwarding direction is simply the data forwarding direction of the node next hop toward the sink.

Note that this field will be set according to the information received in the beacon. Upon the completion of the beaconing phase, every node will build a table about the forwarding direction of its neighbors.

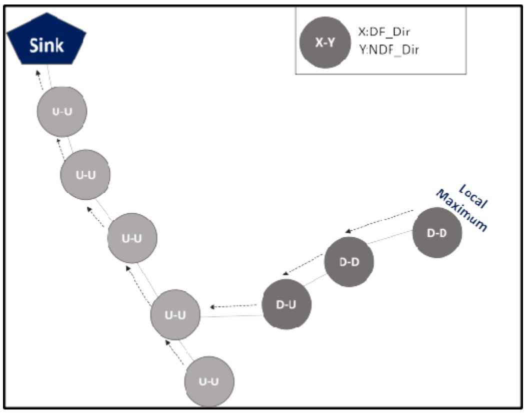

Figure 4: Data Forwarding in VAPR

The data forwarding phase, shown in Figure 4, states that every forwarder has to send the received packets to its neighbors that they have a forwarding direction equal to the forwarder next hop data forwarding direction.

Even though VAPR prevents a data packet from reaching a local maximum node, it periodically requires more amount of information than other protocols to be exchanged. This process is energy consuming and could affect the lifetime of the network.

In the aforementioned routing protocols, energy of sensor nodes weren't considered as a main metric in choosing the potential next hop. For instance, when having two nodes with similar depths but different energy levels, logically the node that has more energy is supposed to be preferred as the next forwarder over the other one. This is not the case in these protocols since their only focus is in data delivery and not energy efficiency.

B. Energy Efficient Routing Protocols

In this section, we introduce the Energy Efficient Routing Protocols which are concerned with maximizing the network lifetime by efficiently using the limited energy budget of sensor nodes. The described protocols focus on solving an energy-related issue called the energy sink-hole problem. This problem occurs when sensors close to the sink, especially the one-hop away ones deplete their energy budget much earlier than the others and thus shutting down the whole network. Two main approaches have been shown to be robust against the energy sink hole problem: either by using a mobile sink to collect reports from sensor nodes or by achieving load balancing using multiple transmission ranges. Further details are provided next. The protocols to be mentioned next are divided into two types according to the sink mobility.

1- Energy Efficient Routing Protocols with Mobile sinks

a) Mobicast

Mobicast, as introduced in [7], is an energy efficient routing protocol. It mainly aims at extending the lifetime of sensors' battery and thus extending the lifetime of the whole network. The key idea of this protocol is to keep sensor nodes in sleep mode unless awakened by Autonomous Underwater Vehicles (AUVs). Sensor nodes in Mobicast are randomly deployed in a 3D manner forming a 3D UWSN. Nodes are then divided into a series of geographical zones called 3D Zone of Reference (3D ZOR) that is visited by the AUV according to a predefined routing path.

Due to the harsh characteristics of the underwater environment, such as propagation delay and low bandwidth, and the long time a sensor node needs to wake up after a period of sleep, sensors need to wake up prior the arrival of the AUV to its ZOR. For this reason, when the AUV is in a certain ZOR, it sends a mobicast

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message to the next ZOR with the purpose of waking up the sleeping nodes. Water current is another characteristic of the underwater environment that was taken into account in Mobicast which mainly results in moving sensor nodes and thus preventing them from receiving the mobicast message and thus creating a 3D hole problem.

In order to solve the hole problem, a 3D Zone of Forwarding (ZOF) is introduced which is usually a zone with an equal or larger size than a 3D ZOR. ZOF is the group of sensor nodes that are responsible for forwarding the mobicast message and hence guarantee that sensor nodes in the next 3D ZOR successfully wake up. The size of the ZOF is critical and should be carefully chosen according to the size and density of the network. For instance, an extremely large ZOF would prevent the hole problem but will consume more energy of sensor nodes in the ZOF.

In sparse networks, there will be a need to use the largest size of ZOF in order to guarantee reaching all sensor nodes. This could negate the main purpose of the Mobicast protocol which is achieving an energy efficient use of the limited battery budget of the sensor nodes in the network.

b) Sparsity-Aware Energy Efficient Clustering Protocol (SEEC)

Sparsity-Aware Energy Efficient Clustering Protocol, as introduced in [8], is another energy efficient routing protocol. The network is divided into ten regions and the sensors are randomly deployed afterwards. Then, Sparsity Search algorithm (SSA) and Density Search Algorithm (DSA) are used to categorize every region into either dense or sparse regions.

In dense regions, a cluster head (CH) is assigned which is the sensor node that has the lowest depth and highest residual energy. CHs collect data received from other nodes in the cluster and send them to the only static sink in the network. This sink is placed in the center to be within the transmission range of most of the sensors.

Sparse regions are assigned two mobile sinks with different configurations. The first sink stays within the sparsest region collecting data from its sensor nodes. It moves away from this region only when its last sensor node dies. The other mobile sink rotates between sparse regions starting from the sparsest region and ending with the least sparse one.

Although this protocol saves energy of sensor nodes and extends the lifetime of the network, it has lower throughput compared with the throughput of DBR.

c) AUV-aided Efficient Data-Gathering (AEDG) Routing Protocol

AEDG, as introduced in [9] also uses autonomous underwater vehicles as mobile sinks. The sensor nodes in this protocol are divided into clusters and each cluster is assigned one gateway sensor which is responsible for delivering data packets to the AUV. In order to achieve a load balance between nodes, the delivery role rotates among all of the sensors based on their residual energy and hence the set of gateway nodes is continuously varying.

Although this approach leads to an efficient energy consumption of nodes' energy and thus maximizing network lifetime, assuming one AUV may decrease the throughput in large and wide networks.

2- Energy Efficient Routing Protocols with Static Sinks

a) Reliable and Energy Balanced Routing Algorithm (REBAR)

This protocol, which is introduced in [10], assumes that the sink is static and is in the middle of a hemispheric shape where nodes are distributed around. REBAR's main focus is on avoiding energy sink-hole problem by evenly distributing the load among all sensor nodes in the network. To do so, REBAR limits the broadcast range of each sensor node to a specific area instead of the whole network. Indeed, the optimal size of the broadcast area, which is proportional to the transmission range, is a compromise between

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energy efficiency and reliability. Consequently, authors strive for deriving the optimal transmission range that minimizes the energy consumption while guaranteeing the packet delivery.

In Basic REBAR, the source node calculates the directional vector to the final destination v and stores it along with the Euclidean distance d in the data packet. The data packet also contains a unique packet ID that consists of the source ID and a sequence number. When a data packet is received by a neighboring sensor *i*, it calculates the difference between its distance to the final destination and the distance d attached in the packet. The resulting difference is then compared with a predefined threshold to determine whether to continue forwarding or to discard the packet. The packet is only discarded when it is a duplicate or when the difference between the di and d is greater than the threshold.

Water current can cause sensor nodes to move and thus forming void regions that will disturb the functionality of the REBAR. For this reason, an extended version of REBAR is introduced to overcome the void region. Extended REBAR divides sensor nodes into two disjoint sets i) Boundary Sets and ii) Non Boundary Sets. If a node within the Non Boundary Set receives a packet, it behaves as the basic REBAR. Otherwise if a node within the Boundary Set receives a packet then it forwards the packet to all of its neighbors without checking the distance or vector values.

Indeed, in a sparse network, there will be so many void regions and consequently most of the sensor nodes will belong to the Boundary set. In this case, these sensors will always forward the data packet to the whole network regardless of vector and distance information and thus wasting a large amount of energy.

b) *Routing Design Avoiding Energy Holes in Underwater Acoustic Sensor Networks*

Authors in [11] proposed an approach to avoid energy holes in UWSNs. They assume that sensors and sink are static and are distributed in a circular manner following the shape of a hemisphere.

The protocol aims at avoiding the energy sink-hole problem by allowing each sensor to have two transmission ranges to distribute the load among sensor nodes especially the one-hop away ones. In other words, the traffic generated from a sensor node is divided into two parts and sent using two different transmission ranges. In order to achieve a balanced energy consumption through the network, the authors analytically derive the optimal utilization ratios of every transmission range for every sensor in the network

Using this approach, the traffic load on the sensors, especially the one-hop away ones, is distributed and the network life is maximized. This approach doesn't take into account node mobility due to water current.

c) *Joint Routing and Energy Management in Underwater Acoustic Sensor Networks*

Another energy efficient approach, presented in [12], aims at overcoming the energy sink hole problem, by balancing the energy consumption among all sensors in the network. The approach seeks reaching a uniform energy depletion among all sensor nodes in the network by endowing each sensor node with the optimal number of transmission power levels, n, while taking into consideration the severe characteristics of the underwater environment through the use of the time varying underwater channel model proposed in [12]. Once the adopted underwater channel model is well integrated in their balanced routing strategy, as well as the optimal number of transmission power levels, n, is derived, the authors analytically determine for every node the optimal load weight for each possible transmission power level that leads to a fair energy consumption through the network and hence the sink hole problem is overcome and the network lifetime is maximized.

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III. CONCLUSION

In this paper, we present a review of the most significant underwater routing protocols and classify them according to their purpose. Underwater wireless sensor networks routing protocols can be divided into i) Reliable Data Delivery Protocols, where their main purpose is the successful and reliable data delivery from source to destination, and ii) Energy Efficient Routing Protocols, which aim at maximizing the network lifetime by efficiently using of the limited battery budget of the underwater sensors.

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