PULRP: Path Unaware Layered Routing Protocol for Underwater Sensor Networks

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Abstract—We propose a Path Unaware Layered Routing Protocol (PULRP) for dense underwater 3D sensor networks. An uplink transmission is considered, where a set of underwater sensor nodes report events to the sink node. PULRP algorithm consists of two phases. In the first phase (layering phase), a layering structure is presented which is a set of concentric spheres, around a sink node. The radius of the concentric spheres is chosen based on probability of successful packet forwarding and packet delivery latency. In the second phase (communication phase), we propose a method to choose the intermediate relay nodes and an on the fly routing algorithm for packet delivery from source node to sink node across the chosen relay nodes. The proposed algorithm, PULRP finds the routing path on the fly and hence it does not require any fixed routing table, localization or time synchronization processes. Our findings show that the proposed algorithm has a considerably better successful packet delivery rate compared to the Under Water Diffusion (UWD) algorithm proposed in [1] and Dijkstra’s shortest path algorithm. In addition the delay involved in PULRP is comparable with that of UWD.

I. INTRODUCTION

Underwater Sensor Networks (UWSN) have been used in monitoring aqueous environments for scientific exploration, commercial exploitation and coastline protection [2], [3]. Acoustic communication is the typical physical layer technology in underwater communication. Few major challenges in the development of UWSN routing protocol are high propagation delay, heavy multipath fading, varying network topology due to mobility and frequent losses of connectivity due to underwater currents and streams [4].

Considering all these issues, we propose a novel PULRP algorithm for dense underwater sensor networks. PULRP has two phases, namely layering phase and communication phase. During layering phase, concentric layers of spheres are formed around the sink node with each node belonging to only one of the spherical layers. The radius of spheres is chosen based on probability of successful packet forwarding and packet delivery latency. In communication phase, routing path is determined on the fly, from source to sink node across the concentric layers.

II. SYSTEM MODEL

We consider a densely deployed 3D underwater sensor network architecture, such that each node is well connected. At real time, each ad hoc sensor unit monitors local underwater activities and reports sensed data through multi hop acoustic routes to a distant command center (i.e. sink node). We assume that the nodes are uniformly distributed and the packet length is the same for all nodes. A low traffic scenario is considered. The signal transmission is assumed to be omni-directional. The channel is considered to be reciprocal, as it holds good for dense networks. We also assume that the nodes transmit with equal and fixed power $P$ and a node requires a received power of at least $P_D$ to detect the packet correctly.

A. Propagation Model

Since we consider a short range transmission model with range of few meters, we can assume that the loss due to scattering and refraction is negligible and that sound has near straight line propagation. Hence, the transmission loss in dB at a distance $R$ from the source is [5]

$$TL = 20 \log R + \alpha R$$

where $\alpha$ is the frequency dependent absorption coefficient. The path loss model is

$$PR = \frac{P}{R^2(10^{\alpha/10})}$$

where $PR$ is the received power at distance $R$.

B. Network Model

The total volume occupied by the UWSN in the region of interest is divided into a large amount of small virtual cubes, such that the cube size is almost equivalent to the physical size of the sensor node. Hence, each cube is either empty or occupied by a single node. Therefore, the probability distribution of how these cubes are occupied by each mobile ad hoc node could be modeled as a binomial distribution. This network model is similar to the one considered in [1]. Assuming that the number of such cubes is large, we can apply Poisson approximation to the binomial distribution [6]. If $N$ is the volume density of the nodes, then the probability of $k$ nodes occupying a volume $V$ is given by:

$$Pr[x = k] = \frac{(\int_V N(V')dV')^k}{k!} \exp^{-\int_V N(V')dV'}$$

(3)

Here $\int_V$ indicates the integral over volume $V$. For uniform density, (3) reduces to

$$Pr[x = k] = \frac{(NV)^k}{k!} \exp^{-NV}$$

(4)
III. PROPOSED PULRP ALGORITHM

The proposed protocol consists of two phases: the layering phase and the communication phase.

Layering Phase — The first phase of the proposed protocol is the layering process [7]. The sink node is considered to be the layer 0 node. It will initiate the layering process by sending a layering probe with power $P_l$ (where $P_l < P$), which contains the current layer number (i.e., layer number 0). All those nodes, which receive this probe with receive power at least $P_D$ (detection threshold) will assign themselves as the layer 1 nodes. These nodes will propagate the probe after incrementing the current layer number (i.e., from 0 to 1).

So, by the time the probe reaches the last set of nodes, each node would have been assigned a layer number depending on its distance from the sink. Geometrically, these layers would be concentric spheres around the sink node. The method of finding the layering probe power $P_l$ is described below.

If we choose $P_l = P$, the layer radius would become $R_D$ itself, which is the maximum range of transmission corresponding to power $P$. However, this may not ensure successful packet forwarding from one layer to next layer when the source node is at the extreme boundary of a particular layer. Hence the value of $P_l$ is chosen using (2) as explained below

$$P_l = P_D R_r^2 10^{3-2} \approx 3Rr$$

where $R_r$ is the ring radius which is chosen as explained below.

A. Determination of Layer Radius $R_r$

Let us consider a layering structure with some radius $R_r$ as shown in Fig. 1. Assume a node $T$ in layer $l$ transmits a packet to sink node with maximum attainable range $R_D$ corresponding to receive power $P_D$. According to PULRP, the source node in layer $l$ has to find a potential relay node in layer $l-1$ for successful packet transmission which is a function of two parameters:

- The transmission range $R_D$: when $R_D$ is large, the node can cover maximum range and can find at least one potential relay node in layer $l-1$. However, $R_D$ is limited by $P$, which is fixed.

- The layer ring radius $R_r$: when $R_r$ is very small, $R_D$ can cover maximum range in $l-1$ and hence node $T$ can find a potential relay node. However, smaller $R_r$ leads to larger number of layers and hence larger number of hops, which will increase the packet delivery failure rate, latency as well as collision.

Hence it is essential to find an optimal value of $R_r$.

1) Upper bound on $R_r$: Let us consider a range circle with center $T$ and radius $R_D$ as shown in Fig. 1. The packet from $T$ will be forwarded to the layer $l-1$, only if at least one node is located in the intersection of the range circle and circle of layer $l-1$. Probability of at least one node lying in the intersection area ($P_S^l$) can be determined from (4), as follows

$$P_S^l = 1 - \exp^{-NV}$$

Here $V$ is the volume of the intersecting region and can be geometrically obtained as [8]:

$$V = \frac{\pi R_r^3}{192}[40 - 144\zeta^2 + 128\zeta^3 - 24\zeta^4]$$

where $\zeta$ is the ratio between the two radii, $R_D$ and $R_r$. We can fix a threshold on probability of successful packet forwarding (say $P_{th}$) and the upper bound on $R_r$ i.e., $R_r^{UB}$ can be found out by incorporating the following constraint.

$$P_S^l > P_{th}$$

Choosing $R_r$ much lesser than the upper bound will have the following implications:

- Maximum latency: Maximum latency for a packet at layer $l$ to reach the sink node (layer 0) can be found out as follows. Consider Fig. 2. If a packet is successfully delivered at the sink, the longest path taken by it is shown in Fig. 2. The maximum latency is approximately equal to

$$T_{max} \approx l(R_D/v + \tau + T_{oth})$$

In (8) the first term $R_D/v$ accounts for the propagation delay. The second term $\tau$ is the constant waiting time at the transmitting node between the request packet and the data packet. $\tau$ is fixed as slightly greater than $2R_r/v$ for proper reception and to avoid collisions. The third term $T_{oth}$ consists of all other delays, such as transmission delay, processing delay, etc. Though $\tau$ in (8) reduces as $R_r$ decreases, the value of $l$ increases, thus, increasing the maximum latency.

- Probability of failure: By using independence assumption in (6) the probability that a packet from layer $l$ does not reach the sink is

$$P_{lf} = 1 - (1 - \exp^{-NV})^l$$

It is clear that as $l$ increases (which is the implication of reducing $R_r$), the packet failure probability will also increase.
Collision: If $R_r$ reduces, there is a chance that the transmission request will cross more than one layer and hence there could be collisions.

Therefore it is advisable to choose the value of $R_r$ in a close neighborhood of $R_r^{UB}$ i.e., $R_r = cR_r^{UB}$ where $c$ is a constant close to 1. From the above selected $R_r$, we can find $P_1$ using (5). The layer number may have to be updated frequently (‘re-layering’) to cater to the mobility of nodes. In PULRP, re-layering starts from the sink node. Whenever the sink node receives a data packet, it will send an ACK. This acts as a probe for the re-layering process for layer 1 nodes. However for higher layers, the data packet transmission request itself acts as the probe for re-layering. Also, the nodes change their layer number, only if they hear the probe three times from the lower layer, in order to avoid glitches in the re-layering process [1]. This implies that ‘re-layering’ is done for every three packets successfully received at the sink node. Also, in this paper, we assume that the node density remains uniform in all layers.

Communication Phase – The communication between any source node ‘$T_1$’ and sink node ‘$S$’ will occur through potential relay nodes across the layers. A potential relay node will be selected from each layer such that the distance between relay nodes are maximum and every selected relay node has sufficient energy for packet transmission. The selection of potential relay nodes is explained in this section.

B. Selection of Potential Relay Nodes

The source node ‘$T_1$’ at layer $l$ will send a control packet. Some node ‘$A$’ in layer $l−1$ will declare itself as the farthest node if it does not overhear any other farthest node declaration until time $t_A$. $t_A$ is the minimum waiting time of node ‘$A$’ which is adjusted according to its distance from the source as explained below.

Theorem 1: Upper bound on distance between two nodes in UWSN is proportional to the difference in received powers from a common source.

Proof: Assume that $P_{R_1}$ and $P_{R_2}$ are the received powers at two nodes, which are at distances $R_1$ and $R_2$, respectively, in a straight line, $(R_1 > R_2)$ from the transmitter. Now using (1), we can write

$$P_{R_2} - P_{R_1} = (R_1 - R_2)\alpha - 20\log \left(1 - \frac{R_1 - R_2}{R_1} \right)$$

As $R_1 > R_2$, $R_1 - R_2 < R_1$ and hence, the second term in RHS of (9) is always negative. Therefore

$$P_{R_2} - P_{R_1} > (R_1 - R_2)\alpha$$
$$\Rightarrow (R_1 - R_2)^{UB} = (P_{R_2} - P_{R_1})/\alpha$$
$$\Rightarrow (R_1 - R_2)^{UB} \propto (P_{R_2} - P_{R_1}) \tag{10}$$

Theorem 2: For farthest node declaration, minimum waiting time of a node which receives power $P_R$ from source node is proportional to $P_R - P_D$.

Proof: Assume that a node $T_1$ in layer $l$ is transmitting. Two nodes in layer $l - 1$, which are in a perpendicular line with node $T_1$ and at distances $R_1$ and $R_2$ $(R_1 > R_2)$ receive the packet as shown in Fig. 3. We know that the time taken for sound to travel a round trip distance of $(R_1 - R_2)$ is $2(R_1 - R_2)/v$, where $v$ is the speed of sound in water. Therefore we can conclude that a node at a distance $R_2$ should at least wait for

$$\frac{2(R_1 - R_2)}{v} \tag{11}$$

before declaring itself as farthest node to $T_1$. However, (11) is in terms of two ranges i.e., $R_1$, $R_2$. To avoid the need to have knowledge of $R_1$ and $R_2$ in order to compute the waiting time, we derive the waiting time of any node in terms of its received power $P_R$, and detection threshold, $P_D$.

Let $P_D$ be the minimum detection threshold, which corresponds to a distance $R_D$. From (10) and (11) we can deduce that any node which receives a power $P_R$ should have a waiting time proportional to $P_R - P_D$ to know whether some node is farther than itself. Therefore, a node which receives power $P_R$ should wait for a time equal to

$$\lambda(P_R - P_D) \tag{12}$$

before declaring itself as the farthest node. In (12) $\lambda$ is the proportionality constant. The parameter $\lambda$ can be estimated as follows. Let the node $B$ be at the inner boundary of layer $l - 1$ at a distance $R_D$ from $T_1$, as shown in Fig. 3. Also assume that the node $A$ is at the outer boundary of layer $l - 1$. Hence the distance from $T_1$ to $A$ is $R_D - R_r$, and the distance between $A$ and $B$ is $R_r$. Let the received power at node $A$ be $P_T$. The waiting time obtained from (11) (with $R_1 - R_2 = R_r$) is the minimum waiting time for node $A$, while (12) is the actual
waiting time in PULRP. Therefore from (11) and (12)
\[ \lambda (P_R - P_D) \geq 2R_r/v \]
\[ \Rightarrow \lambda \geq \frac{2R_r}{v(P_R - P_D)} \]  
(13)
Assume the range corresponding to \( P_R \) is \( R \), then from (2)
\[ P_R - P_D = \alpha y + 20 \log \left( \frac{R_D}{R_D - y} \right) \]  
(14)
Substituting (14) in (13) we get
\[ \lambda \geq \frac{2R_r}{v(\alpha y + 20 \log \left( \frac{R_D}{R_D - y} \right))} \]  
(15)
Since \( y = R_D - R \) is less than \( R_D \), it is clear that as \( y \) increases
the RHS of (15) decreases. Therefore, the minimum value of \( \lambda (\lambda_{min}) \) can be obtained by substituting the maximum value
for \( y \) which is \( R_r \) (we can see from Fig. 3 that, in the worst case,
the node \( T_1 \) can be at the outer edge of layer \( l \), hence
the maximum value that \( y \) can take is \( R_r \)). Therefore
\[ \lambda_{min} = \frac{2R_r}{v(\alpha(R_D - R_r) + 20 \log \left( \frac{R_D}{R_D - R_r} \right))} \]
If \( \lambda \) is much larger, it will increase the latency in the network.
So it is better to take \( \lambda \) in close proximity of \( \lambda_{min} \).

Hence the minimum waiting time of a node to declare itself
as farthest node is
\[ \lambda (P_R - P_D) \]  
(16)
However, (16) does not have energy parameters. Therefore the
selected potential relay nodes may have very less residual
energy and hence the packet delivery may fail. To avoid this
we reformulate the minimum waiting time of nodes as:
\[ \lambda (P_R - P_D)/\nu \]  
(17)
where \( \nu \) is the energy factor, i.e. the fraction of the energy
remaining in the node to the total energy. (17) will ensure that
the energy consumption in various nodes are almost equal.

The above determined farthest node in layer \( l - 1 \) becomes
the potential relay node for a source node \( T_1 \) of layer \( l \). In
a similar manner, the hence chosen potential relay node of
layer \( l - 1 \) acts as source for the potential relay node in layer
\( l - 2 \). The procedure is repeated until the packet is propagated
to the sink.

IV. SUMMARY OF PROPOSED PULRP ALGORITHM

The method of determining the path from source node \( A \) to
the sink node \( S \) in PULRP is described below:

1) Node ‘A’ broadcasts a control packet, which contains the
source ID, the destination ID, packet ID and the spreading
code which will be used for the data packet transmission.
This is transmitted using a common spreading code. If this control packet is received properly (i.e. no
other node in the neighborhood tries to send a control
packet simultaneously), a collision free transmission will be ensured.

2) On receiving the control packet, the potential relay node in the lower layer, say ‘B’, will respond with an ACK. Once the potential relay node
is identified, all other nodes can go back to sleep.

3) A particular interval (\( \tau \), the estimation of which is explained in Section III-A) after the control packet is transmitted, the source sends the data packet. If
the node ‘B’ successfully receives the packet, node ‘B’ will broadcast control packet to find out its next
potential relay node (towards the destination), as in
Step 1. The broadcast control packet from node ‘B’
acts as an acknowledgment for ‘A’. If node ‘A’ does not
receive the B’s broadcast control packet message, then
it will broadcast the control packet as in Step 1 and the
process will be repeated, until the packet reaches the
destination.

V. SIMULATION RESULTS

Extensive simulations have been carried out to evaluate the
performance of PULRP. The parameters used for evaluation
are the success rate and average delay. The success rate is
defined as the ratio of total packets delivered to the sink to
the total packets generated in the sources. The average delay
is the average end to end delay for each packet delivered to
the sink.

An underwater cubical space of \( 100m \times 100m \times 100m \), is
considered where the nodes are uniformly deployed. The sink
is always fixed at (100, 100, 100). All the nodes in the outer
most layer are selected as source nodes. The packet generation
is a Poisson process with mean 10 sec, and the simulation
is carried out for a period of 20 minutes. A random walk
mobility model with average speed of 1.5m/s [1] is used in
the simulation. We have used the energy propagation model
as suggested in (1) with \( \alpha = 0.7dB/m^3 \) [5]. The medium
access is CDMA with eight spreading codes.

Fig. 4 and Fig. 5 shows the comparison of PULRP algorithm
with that of the Dijkstra’s shortest path routing algorithm with
distance as routing metric and underwater diffusion algorithm
(UWD) proposed in [1] for various node densities. Note that
in the shortest path algorithm, the shortest path is computed only once at the start of the simulation. From Fig. 4 we can observe that the success rate in PULRP is more as compared to the other two algorithms at all node densities. This can be attributed to the freedom of choice of selecting the ring radius and the equal energy distribution in the PULRP algorithm. Furthermore, the end-to-end delay in the case of PULRP is almost equal to UWD. Although average delay is minimum for the shortest path algorithm, its success rate is many orders lower than that of the other two algorithms. This is because, due to mobility, the estimated shortest path changes, resulting in packet loss. As PULRP outperforms UWD and shortest path algorithm we have analyzed the performance of PULRP for various parameters in the following paragraphs.

Fig. 6 shows the graph between success rate and the packet forwarding probability threshold \( P_{th} \) for various node deployment densities of PULRP. For each density, the \( R_r \) is kept as \( 0.99 \times R_r^{UB} \) (i.e., \( \epsilon = 0.99 \)). It can be seen that the success rate will increase as \( P_{th} \) increases for all values of node densities. Furthermore, as the node density increases the performance of algorithm increases to a large extent.

Fig. 7 shows the success rate and the average delay for various choices of the ring radius. The ring radius is decreased from \( R_r^{UB} \) to \( 0.55 \times R_r^{UB} \). Here we can see that for fixed \( P \), the success rate increases as the ring radius decreases, at the same time increasing the average delay.

VI. CONCLUSIONS

We have proposed a novel on-the-fly PULRP algorithm for underwater sensor networks. PULRP ensures a high success rate by selecting potential relay nodes which have sufficient energy for packet forwarding. The proposed protocol does not require localization, time-synchronization or routing-table maintenance. The on-the-fly nature of PULRP makes it robust against issues like multipath or loss of connectivity due to node mobility or underwater currents. We have shown that PULRP has better successful packet transmission rate compared to UWD and shortest path algorithm. Also, the end-to-end delay involved in PULRP is comparable to that of UWD. We have also analyzed the performance of the proposed protocol in terms of packet transmission success rate for various probability of forwarding threshold \( (P_{th}) \) values. The relationships between the packet transmission success rate, end-to-end delay and ring radius \( R_r \) have also been discussed. The statistical analysis of the route duration, route length and success rate are being considered for further research.

REFERENCES