

# DATUM: Dynamic Topology Control for Underwater Wireless Multimedia Sensor Networks

Sudip Misra<sup>‡</sup>, Senior Member, IEEE, Anudipa Mondal<sup>†</sup>, and Ayan Mondal<sup>‡</sup>, Student Member, IEEE

<sup>‡</sup>Department of Computer Science and Engineering, Indian Institute of Technology Kharagpur, India

<sup>†</sup>Advanced Technology Development Centre, Indian Institute of Technology Kharagpur, India

Email: <sup>‡</sup>{smisra, ayanmondal}@sit.iitkgp.ac.in; <sup>†</sup>anudipa.mondal@iitkgp.ac.in

**Abstract**—In this paper, the problem of dynamic topology management in underwater wireless multimedia sensor networks (UWMSNs) in the presence of underwater wireless multimedia sensor nodes is studied using cooperation game theory. In the existing literature, researchers focused on the efficient management of underwater sensor networks and terrestrial wireless multimedia sensor networks. However, in the presence of underwater multimedia wireless sensor nodes, the amount of data to be transmitted increases significantly which deteriorates the overall network performance. Hence, there is a need to design a delay-optimal dynamic topology control scheme for UWMSNs, while maximizing the network throughput and lifetime. In this work, we propose a cooperative game theory-based scheme, named DATUM, for dynamic topology control. In DATUM, initially, we explore the feasible data transmission path available from the source node at seabed to the sink node at the surface of the ocean. Thereafter, using cooperation game theory, we identify the set of optimal paths to be selected. Finally, in DATUM, each underwater wireless multimedia sensor node decides its optimum transmission communication range for maximizing the network lifetime, while ensuring the network connectivity. Through simulation, we observed that using DATUM, network delay reduces by 30.74 percent, while the network lifetime increases by 59.61 percent.

**Index Terms**—Topology control, Underwater wireless multimedia sensor networks (UWMSNs), Cooperation, Game theory, Network lifetime

## I. INTRODUCTION

Underwater wireless sensor networks (UWSNs) [1] are envisioned to monitor a specific geographically located body of water. In modern days, UWSNs have multiple applications such as exploring marine, monitoring underwater pollution, navigation of autonomous underwater vehicles (AUVs), and collecting marine-data. In existing literature, the researchers proposed several architecture and scheme for underwater environment. However, most of these works focused on UWSNs with scalar sensor nodes. With the advancement of multimedia technology, there is need to provide multimedia information with the scalar data in order enhance the experience of coastal surveillance and underwater exploration. With the existing UWSN architecture, we cannot ensure the delivery of multimedia data with quality of service (QoS) such as less delay and high throughput. In this work, the problem of multimedia data delivery with less delay and high throughput in UWSNs with multimedia sensor nodes, termed as *underwater wireless multimedia sensor networks* (UWMSNs), is addressed.

The topology control schemes designed for terrestrial wireless multimedia sensor networks (WMSNs) cannot be applied in UWMSNs due to the presence of vast differences in the environment of terrestrial and underwater scenarios. Unlike traditional multimedia sensor networks, the performance of UWMSNs gets affected by several parameters such as variable propagation delay, low bandwidth capacity, multi-path fading, shadow loss, and Doppler spreading, as UWMSNs use acoustic communication. Hence, underwater multimedia communication is very challenging. On the other hand, the multimedia sensor nodes are costly and the multimedia communication consumes high energy. Therefore, there is a need to design scheme while satisfying that the network of sparsely-deployed multimedia sensor nodes are connected and network lifetime is high. Furthermore, the passive mobility of the underwater multimedia sensor nodes depends according to the presence of waves or currents in the underwater environment. Additionally, QoS of underwater multimedia communication depends on the acoustic links, i.e., transmission power level. QoS of these acoustic links depends on different factors such as seabed sediment, water temperature, depth of the nodes and ambient noise. In existing literature, a few works are there on underwater multimedia sensor networks, viz. [2], [3]. However, to the best of our knowledge, there is no work done on topology control for UWMSNs in existing literature. Additionally, the topology control schemes [4], [5] designed for the UWSNs cannot be used as the multimedia nodes are sparsely deployed. Hence, there is a need of design scheme for topology management while ensuring less delay, high throughput, and high network lifetime.

In this paper, we propose a game theory-based dynamic topology control scheme, named *DATUM*, for maximizing throughput and network lifetime with minimum network delay in UWMSNs in the presence of multimedia sensor nodes. We use a cooperation game theoretic approach to decide the optimal set of paths for minimizing delay and maximizing throughput and optimal transmission power for maximizing network lifetime. Initially, we explore the available paths for multimedia communication using a brute-force approach. Thereafter, we determine a preference relation among the paths with cooperation game and select an optimal set of paths. Finally, in order to maximize the network lifetime, we determine the optimal transmission power of the underwater multimedia sensor nodes in the selected paths. In summary,

the specific contributions of this paper are as follows:

- 1) We present a dynamic topology control (DATUM) scheme for UWMSNs in order to maximize network throughput and lifetime with minimal delay.
- 2) Cooperative game theory is used to select the optimal set of paths and decide optimal transmission power level for the selected node while ensuring the aforementioned properties.
- 3) We present three algorithms in DATUM. The first algorithm uses a brute-force approach and explores the available paths from the source node to the surface buoys. Using the second algorithm, the surface buoys select the optimal set of paths. Using the final algorithm, the optimal transmission power is decided by the underwater multimedia sensor nodes.

## II. RELATED WORK

In recent years, several works have been done in wireless sensor networks in the underwater environment. In many research work, the problem of topology control has been addressed. Coutinho *et al.* [1] surveyed the challenge of managing topology and localization of underwater sensor nodes. The challenge of synchronization and localization of underwater sensor nodes is focused in [4] while proposing a tracking algorithm to improve the localization accuracy. Caruso *et al.* [5] considered network connectivity in the presence of mobility in underwater sensor networks. But in their proposed algorithm the delay-tolerant routing is absent. Misra *et al.* [6] proposed a game theory based topology control algorithm for underwater sensor nodes in an oligopolistic environment using the unlocalized nodes as a leader and the localized nodes as the followers. The proposed topology management algorithm follows Single-Leader-Multi-Follower Stackelberg game theory. Ojha *et al.* [7] proposed the 3-dimensional localization scheme for underwater mobile nodes where the source nodes can accurately determine the location of unlocalized sensor nodes by sending a beacon message. Thus they can predict the mobility of the sensor nodes. In another work, Ojha *et al.* [8] proposed the Tic-Tac-Toe Architecture that maintains the connectivity from a source node to sink nodes in the underwater sensor networks. Coutinho *et al.* [9] proposed a geographic routing protocol and topology control protocol where underwater sensor networks follow the SEA swarm architecture for selecting the next-hop forward node. On the other hand, in a terrestrial environment, there are a few works, viz. [10], [11], on topology management in wireless multimedia sensor networks. Misra *et al.* [10] proposed the placement and connectivity of both the camera sensor nodes and the scalar sensor nodes using coalition formation game.

Pompili *et al.* [2], [3] proposed a cross-layer underwater framework to optimize the underwater multimedia communication between limited-bandwidth and less battery energy devices in the underwater acoustic channel. Liu *et al.* [12] introduced a multipath routing algorithm based on the LEACH algorithm. Their proposed algorithm increases network lifetime by considering the distance and energy at the time of

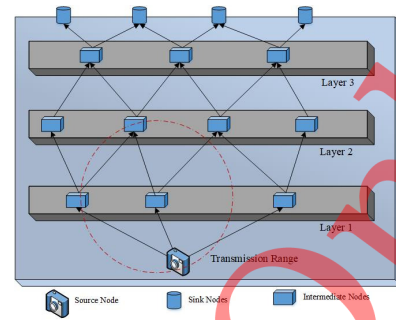


Fig. 1. Schematic Diagram of Multi-Layered UWMSN

choosing a transmission path. Hsu *et al.* [13] proposed a crossed layered MAC protocol for improving the communication latency and network throughput where the underwater channel is divided into some super-frames of fixed length. Ze *et al.* [14] proposed a routing protocol for underwater multimedia data transmission where the multimedia data transmission happens block-wise through different layers. In existing literature, researchers proposed few hybrid approaches such as Load Balanced Multicast Routing Protocol (LBMRP) [15] and Segmented Data Reliable Transfer (SDRT) [16]. LBMRP [15] increases the network lifetime with balancing the network overhead and SDRT [16] reduces the number of transmission packets through the sensor nodes. Luo *et al.* [17] proposed a routing scheme for oceanic sensor networks, named DR-OSNs, while considering the underwater communication channels. Webster *et al.* [18] proposed a swarm-based algorithm for location independent underwater nodes for determining optimal overhead in underwater wireless sensor networks. A localization based routing protocol was proposed for forwarding data packet to the sink nodes using the location information and the residual energy of the underwater sensor nodes by applying a new greedy approach [19]. Similar work is done by Kohli *et al.* [20] for improving network lifetime and minimizing energy consumption by using greedy routing protocol in underwater wireless sensor networks.

However, none of these works focus on the topology management for UWMSNs. As mentioned earlier, the topology management schemes proposed for terrestrial WMSNs cannot be applied to UWMSNs due to oceanic properties. Additionally, the schemes proposed for UWMSNs are not applicable due to the energy constrained nature of the underwater multimedia sensor nodes. Hence, there is a need to design a topology control scheme for UWMSNs while considering the dynamic architecture.

## III. SYSTEM MODEL

We consider a multi-layered two-dimensional UWMSN consisting of a multiple underwater wireless multimedia sensor node at the sea-bed, multiple intermediate underwater wireless multimedia sensor nodes, and multiple surface buoys as shown in Figure 1. We consider that each underwater multimedia sensor node is capable of communicating at least one underwater multimedia sensor node which is placed at a higher

layer. The surface buoys act as the sink nodes in UWMSN. Here, we consider that each underwater multimedia sensor node  $n_{i,l} \in \mathcal{N}$  of layer  $l \in \mathcal{L}$ , where  $\mathcal{N}$  is the set of underwater multimedia sensor nodes and  $\mathcal{L}$  is the set of layers in UWMSN while considering that underwater multimedia sensor nodes at the sea-bed belongs to *Layer 0*, can communicate with underwater multimedia sensor node  $n_{j,(l+1)}$ , if and only if node  $n_{j,(l+1)}$  is within the communication range  $R_i$  of node  $n_{i,l}$ . We consider that two layers  $l$  and  $(l+1)$  are separated by a perpendicular distance of  $D_{l,(l+1)}$ . In other words, we can represent the UWMSN as a directional graph  $G(\mathcal{N}, E)$ , where each edge  $e_{[i,l],[j,(l+1)]} \in E$  is represented as follows:

$$e_{[i,l],[j,(l+1)]} = \begin{cases} 1, & \text{if } d_{[i,l],[j,(l+1)]} \leq R_i \\ 0, & \text{otherwise} \end{cases} \quad (1)$$

where  $d_{[i,l],[j,(l+1)]}$  denotes the distance between the nodes  $n_{i,l}$  and  $n_{j,(l+1)}$ . Additionally, we define  $e_{[j,(l+1)],[i,l]} = -1$ , if  $d_{[i,l],[j,(l+1)]} \leq R_i$ . Moreover, we consider that each underwater wireless multimedia sensor node  $n_{i,(|\mathcal{L}|-1)}$  is connected to at least one surface buoy, i.e., sink node. We define the neighbor list  $NL_s$  of each surface buoy  $s \in \mathcal{S}$ , where  $\mathcal{S}$  is the set of surface buoys, as follows:

$$NL_s = \{n_{i,(|\mathcal{L}|-1)} | d_{(i,(|\mathcal{L}|-1)),s} \leq R_s\} \quad (2)$$

where  $R_s$  is the maximum communication range of surface buoy  $s$ , and  $d_{(i,(|\mathcal{L}|-1)),s}$  is the distance between surface buoy  $s$  and the multimedia sensor node  $i$  at Layer  $(|\mathcal{L}|-1)$ .

On the other hand, we consider that each underwater wireless multimedia sensor node is capable of adjusting transmission power. Each node  $n_{i,l}$  with transmission power  $P_i$  has a communication range of  $R_i$ . Here, the mapping function  $f : P_i \rightarrow R_i$  has an one-to-one relation, where  $0 < P_i \leq P_{max}$  and  $P_{max}$  is the maximum transmission power level. In this work, we consider that the submerged wireless multimedia sensor nodes follow a meandering mobility model with a peak velocity of 0.3 m/s [5]. These nodes having a maximum amount of energy  $E_{max}$  are energy constrained in nature. However, we consider that the surface buoys can communicate with base-station directly.

**Assumptions:** The assumptions considered in the proposed scheme, DATUM, are as follows:

- Each wireless multimedia sensor node at the seabed is treated separately.
- Possible paths from a source node to the sink nodes are explored using a brute-force approach. Here, the explored area resembles a conical shape as shown in Figure 1.
- The deployed wireless multimedia sensor nodes and the surface buoys are cooperative in nature.
- Due to energy constraint nature of the wireless multimedia sensor nodes, these nodes are set free from any computational complexity. Additionally, we consider that the decisions are made by the surface buoys based in the computation performed at their end.

## IV. DATUM: THE PROPOSED DYNAMIC TOPOLOGY CONTROL SCHEME

### A. Game formulation

To study the interaction among the underwater multimedia sensor nodes and the surface buoys, we use a cooperative game theory [10]. In DATUM, firstly, each underwater multimedia sensor node explores its neighbor node by sending a HELLO message, as shown in Figure 2. After receiving, each node replies with HELLO\_ACK message, as shown in Figure 2. Based on this information, the nodes update their neighbor list. Thereafter, each node sends a REQ message (as shown in Figure 2) to the neighbor nodes at a higher level. After receiving the REQ messages, the surface buoys decide the optimal paths be selected, cooperatively. Next, the surface buoys send the REP messages (as shown in Figure 2) to the selected underwater multimedia sensor nodes. Thereafter, each selected underwater multimedia sensor node reduces to an optimal transmission power level for maximizing network lifetime using cooperation game theory. In DATUM, each surface buoy  $s$  calculates payoff value of each path available from it to the source wireless multimedia sensor node, with an objective to maximize the overall payoff value. The payoff value for each path  $p \in \mathcal{P}$ , where  $\mathcal{P}$  is the set of available paths explored using brute-force approach, calculated by the surface buoys is discussed in detail in Section IV-A.

### Utility Function For Each Path

The utility function  $\mathcal{U}_{s,p}(\cdot)$  for each path  $p$  signifies the QoS of the path. In DATUM, we consider that the underwater wireless sensor nodes are homogeneous in nature, i.e., the maximum capacity of each node is same. We consider that  $\mathcal{U}_{s,p}(\cdot)$  depends on the residual energy  $E_i^{res}$  of the intermediate node  $n_{i,l}$ , time to disconnect  $\tau_{i,j}$  of two intermediate nodes  $n_{i,l}$  and  $n_{j,(l+1)}$ , and Euclidean distance  $d_{i,j}$  between two intermediate nodes  $n_{i,l}$  and  $n_{j,(l+1)}$ , where  $d_{i,j} \equiv d_{[i,l],[j,(l+1)]}$ .

**Residual Energy ( $E_i^{res}$ ):** Residual energy  $E_i^{res}$  of node  $n_{i,l}$  at Layer  $l$  signifies the lifetime of the node. Hence, each surface buoy aims to select the nodes with residual energy. Therefore, we consider that the payoff of the utility function  $\mathcal{U}_{s,p}(\cdot)$  varies proportionally with  $E_i^{res}$ .

**Time to disconnect ( $\tau_{i,j}$ ):** With the increase in time of disconnect  $\tau_{i,j}$  of two intermediate nodes  $n_{i,l}$  and  $n_{j,(l+1)}$ , the payoff of the utility function  $\mathcal{U}_{s,p}(\cdot)$ . Increase in  $\tau_{i,j}$  signifies that nodes  $n_{i,l}$  and  $n_{j,(l+1)}$  can communicate for a longer duration, i.e., the topology remains unaffected. From Figure 3, we calculate  $\tau_{i,j}$  as follows:

$$\tau_{i,j} = \begin{cases} \frac{1}{\nu_{j,(l+1)}} D_{l,(l+1)} [\cot \alpha + \cot \beta] & \text{if } n_{j,(l+1)} \text{ is at A} \\ \frac{1}{\nu_{j,(l+1)}} D_{l,(l+1)} [\cot \alpha - \cot \beta] & \text{if } n_{j,(l+1)} \text{ is at A'} \end{cases} \quad (3)$$

where  $\nu_{j,(l+1)}$  denotes the average velocity of node  $j$  at Layer  $(l+1)$ ,  $\alpha = \sin^{-1} \left( \frac{D_{l,(l+1)}}{R_i} \right)$  and  $\beta = \sin^{-1} \left( \frac{D_{l,(l+1)}}{d_{i,j}} \right)$ .

**Euclidean distance ( $d_{i,j}$ ):** With the increase in Euclidean distance  $d_{i,j}$  of two intermediate nodes  $n_{i,l}$  and  $n_{j,(l+1)}$ , the

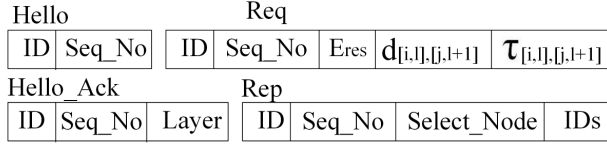


Fig. 2. Packet Formats

payoff of the utility function  $\mathcal{U}_{s,p}(\cdot)$  decreases due to increase in communication delay. We calculate  $d_{i,j}$  as follows:

$$d_{i,j} = \sqrt{(x_{n_{j,(l+1)}} - x_{n_{i,l}})^2 + (y_{n_{j,(l+1)}} - y_{n_{i,l}})^2} \quad (4)$$

where  $(x_{n_{i,l}}, y_{n_{i,l}})$  denotes the Cartesian coordinate of underwater multimedia sensor node  $n_{i,l}$ .

Therefore, we define the utility function  $\mathcal{U}_{s,p}(\cdot)$  as follows:

$$\mathcal{U}_{s,p}(\cdot) = |\mathcal{L}| \left( \prod_{n_{i,l}} \frac{E_i^{res}}{E_{max}} + \prod_{n_{j,(l+1)}} \frac{\tau_{i,j}}{\tau_{max}} - \prod_{n_{i,l}, n_{j,(l+1)}} \frac{d_{i,j}}{R_{max}} \right) \quad (5)$$

where  $n_{i,l}, n_{j,(l+1)} \in \mathcal{N}_p$ ,  $\mathcal{N}_p$  denotes the set of underwater multimedia sensor nodes in path  $p$  and  $|\mathcal{N}_p| = (|\mathcal{L}| + 1)$ ,  $\tau_{max} = 2 \cot \alpha$ , and  $R_{max}$  defines the communication range of a sensor node with the maximum transmission power  $P_{max}$ . The surface buoys try to maximize the payoff value while satisfying the following constraints —

$$E_i^{res} \geq E_{th}, \quad \tau_{i,j} \geq \tau_{th}, \quad \text{and} \quad d_{i,j} \leq R_i \quad (6)$$

where  $E_{th}$  and  $\tau_{th}$  represent the threshold values for residual energy and time to disconnect, respectively.

### Utility Function For Each Node

Given the set of selected paths  $\mathcal{P}_s \subseteq \mathcal{P}$  by the surface buoys, each node  $n_{i,l}$  which belongs to a path  $p \in \mathcal{P}_s$ , tries to optimize the transmission power level. The utility function  $\mathcal{B}_{i,l}(\cdot)$  signifies an optimal trade-off between the increase in network lifetime and decrease in network connectivity. We define  $\mathcal{B}_{i,l}(\cdot)$  as follows:

$$\mathcal{B}_{i,l}(\cdot) = \sum_{n_{j,(l+1)} \in \mathcal{N}_p} \left( \frac{\tau_{th}}{\tau_{i,j}} + \frac{d_{i,j}}{D_{l,(l+1)}} \right), \forall p \in \mathcal{P}_s \quad (7)$$

Each node  $n_{i,l}$  tries to maximize the payoff of utility function  $\mathcal{B}_{i,l}(\cdot)$ , while satisfying the following constraint in addition to the constraints mentioned in Equation (6) —

$$R_i > D_{l,(l+1)} \quad \text{and} \quad R_i \geq (d_{i,j}, \forall n_{j,(l+1)} \in \mathcal{N}_p) \quad (8)$$

### B. Solution for DATUM

In DATUM, we define a preference relation among the choices. For example, we have two strategies or paths  $p_A$  and  $p_B$ . We consider that  $p_A \prec p_B$ , if and only if we have  $\mathcal{U}_{s,p_B}(\cdot) > \mathcal{U}_{s,p_A}(\cdot)$ . Similarly, the surface buoys define preference relations among the explored paths and select the optimal number of paths defined a priori. Hence, we argue

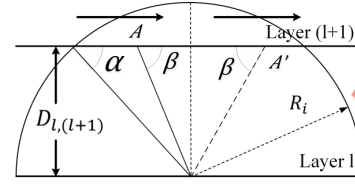


Fig. 3. Time To Disconnect

that in DATUM, there exists an equilibrium point, which is the equilibrium solution.

On the other hand, each node decides its optimum transmission range based on the preference relation —  $R_i \prec R_i^*$ , where  $\mathcal{B}_{i,l}(R_i) < \mathcal{B}_{i,l}(R_i^*)$ . Therefore, we argue that the proposed scheme, DATUM, ensures an increase in lifetime as  $R_i^* \leq R_{max}$ .

### C. Algorithms

In DATUM, Algorithm 1 deals with exploring the available paths for the source nodes at the seabed to the surface buoys using brute-force approach, e.g. Depth First Search (DFS) algorithm. Thereafter, using Algorithm 2, the surface buoys select the optimal paths for data transfer. Finally, using Algorithm 3, each underwater multimedia sensor node in the selected paths decide the optimal transmission power, i.e., optimal communication range, in order to maximize the network lifetime. Moreover, the communication range of the nodes which are not in the selected paths is set to zero, i.e., switch to *sleep* mode.

#### Algorithm 1 Exploring Available Paths

##### INPUTS:

- 1:  $\mathcal{N}$   $\triangleright$  Set of available underwater wireless multimedia sensor nodes
- 2:  $\mathcal{L}$   $\triangleright$  Set of Layers
- 3:  $G(\mathcal{N}, E)$   $\triangleright$  Directed Graph with the available edges

##### OUTPUT:

- 1:  $\mathcal{P}$   $\triangleright$  Set of available paths to surface buoys

##### PROCEDURE:

- 1:  $\mathcal{P} \leftarrow \{\emptyset\}$
- 2: **for** Each  $n_{i,0} \in \mathcal{N}$  **do**
- 3:   Use DFS to explore paths to the surface buoys from node  $n_{i,0}$  at seabed and add to  $\mathcal{P}$
- 4: **end for**
- 5: **return**  $\mathcal{P}$

## V. PERFORMANCE EVALUATION

In this section, we analyze the performance of the proposed scheme, DATUM, with the varying number of underwater wireless multimedia sensor nodes.

### A. Simulation Parameters

For simulation, we varied the number of underwater wireless multimedia sensor nodes as mentioned in Table I. We simulated the proposed scheme in MATLAB simulation platform. We consider that each node moves in one direction due to passive mobility with an average velocity of 0.3 m/s. We considered the meandering mobility model for simulation.

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**Algorithm 2** Optimal Path Selection

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**INPUTS:**

- 1:  $\mathcal{N}$   $\triangleright$  Set of available underwater wireless multimedia sensor nodes
- 2:  $\mathcal{L}$   $\triangleright$  Set of Layers
- 3:  $\mathcal{P}$   $\triangleright$  Set of available paths to surface buoys
- 4:  $M$   $\triangleright$  Maximum number of paths to be chosen
- 5:  $E_i^{res}$ ,  $\tau_{i,j}$ ,  $d_{i,j}$  and  $R_i$ ,  $\forall i \in \mathcal{N}$
- 6:  $E_{max}$ ,  $\tau_{max}$ ,  $D_{l,(l+1)}$ ,  $\forall l \in \mathcal{L}$

**OUTPUT:**

- 1:  $\mathcal{P}_s$   $\triangleright$  Set of selected paths

**PROCEDURE:**

- 1: **for** Each  $p \in \mathcal{P}$  **do**
  - 2:     Calculate  $\mathcal{U}_{s,p}(\cdot)$  using Equation (5)
  - 3: **end for**
  - 4: Sort  $\mathcal{U}_{s,p}(\cdot)$ ,  $\forall p \in \mathcal{P}$  in *descending* order
  - 5: Store the values in  $\mathbb{U}$  and corresponding indexes in  $\mathbb{I}$
  - 6:  $k \leftarrow 0$  and  $\mathcal{P}_s \leftarrow \{\emptyset\}$
  - 7: **for** Each  $p \in \mathcal{P}$  **do**
  - 8:     **if**  $k < M$  **then**
  - 9:          $\mathcal{P}_s \leftarrow \mathcal{P}_s \cup \{\mathbb{I}(k)\}$
  - 10:          $k \leftarrow k + 1$
  - 11:     **end if**
  - 12: **end for**
  - 13: **return**  $\mathcal{P}_s$
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**Algorithm 3** Deciding Optimal Transmission Power

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**INPUTS:**

- 1:  $\mathcal{N}$   $\triangleright$  Set of available underwater wireless multimedia sensor nodes
- 2:  $\mathcal{L}$   $\triangleright$  Set of Layers
- 3:  $\mathcal{P}_s$   $\triangleright$  Set of selected paths
- 4:  $\delta$   $\triangleright$  Communication range reduction factor

**OUTPUT:**

- 1:  $R_i^*$ ,  $\forall n_{i,l} \in \mathcal{N}$   $\triangleright$  Optimal Communication Range

**PROCEDURE:**

- 1: **for** Each  $n_{i,l} \in \bigcup_p \mathcal{N}_p$  **do**
  - 2:     Calculate  $\mathcal{B}_{i,l}(R_{max})$  using Equation (7)
  - 3:      $R_i^* \leftarrow R_{max}$
  - 4:     **do**
  - 5:          $R_i \leftarrow R_i^*$
  - 6:          $R_i^* \leftarrow R_i - \delta$
  - 7:         **while**  $\mathcal{B}_{i,l}(R_i^*) \geq \mathcal{B}_{i,l}(R_i)$
  - 8:     **end for**
  - 9: **for** Each  $n_{i,l} \notin \bigcup_p \mathcal{N}_p$  **do**
  - 10:      $R_i^* \leftarrow 0$
  - 11: **end for**
  - 12: **return**  $R_i^*$ ,  $\forall n_{i,l} \in \mathcal{N}$
- 

TABLE I  
SIMULATION PARAMETERS

Parameter	Value
Number of sensor node	50, 100, 200
Number of Surface buoys	10
Number of paths to be chosen	5
Node velocity	0.3 m/s [5]
Mobility model	Meandering mobility model [5]
Initial energy of a node	150 J [8]
Channel Frequency	13 kHz [21]
Communication Range	800 m [21]
Speed of Sound	1514 m/s [5]
Number of Layers	5
Distance between two Layers	0.5 km

**B. Benchmarks**

We evaluated the performance of the proposed scheme, DATUM, by comparing with existing schemes – TttArch [8] and RAND. In TttArch [8], Ojha *et al.* proposed to form a virtual topology by activating few nodes in order to achieve high network lifetime, while ensuring connectivity among the nodes. On the other hand, in RAND, we consider that the paths from the source to the sink nodes are chosen randomly and the nodes in the selected paths communicate with maximum transmission power.

**C. Performance Metrics**

The proposed scheme DATUM is evaluated in terms of the following parameters.

**Network Delay:** We aim to minimize the overall network delay incurred for transmitting multimedia data in the underwater environment. We evaluate the network delay as the total delay incurred in different steps – neighbor finding, path establishment, and data transmission.

**Network Throughput:** With the increase in network throughput, network bandwidth utilization increases. However, the throughput cannot increase beyond certain value due to the limitation of link capacity. We evaluate the network throughput as the average value of total data transmitted in the simulation duration.

**Network Lifetime:** We define network lifetime as the time duration elapsed till the fifty percent of the deployed nodes are exhausted. We argue that an increase in network lifetime signifies the energy efficiency of the proposed scheme.

**D. Results and discussions**

For simulation, we consider that the neighbor node list gets updated in every 10 unit time and the multimedia data packets are of size 2034 bytes. From Figure 2(a), we yield that using DATUM, network delay reduces by 30.74-47.23% than using TttArch and RAND, respectively. We observed that using DATUM, the link failure reduces significantly than using TttArch and RAND. On the other hand, Figure 2(b) depicts that the network throughput is almost the same in case of DATUM and TttArch. However, using RAND, the network throughput decreases significantly.

Figure 2(c) depicts that the number of nodes activated in the network. We observed that with the increase in the number of nodes deployed in the network, the number of activated nodes decreases significantly using DATUM than using TttArch and RAND. Due to the fact that using DATUM, the nodes which are part of the selected paths are activated and the other nodes are in sleep mode. Additionally, from Figure 2(d), we observed that the network lifetime increases by 59.61-79.51% than using TttArch and RAND. Using DATUM, the energy consumption reduces due to following reasons – (1) less number of activated nodes and (2) optimal transmission power level of the activated nodes.

Therefore, we argue that the proposed scheme, DATUM, enhances the performance of UWMSN holistically, i.e., network-lifetime and network throughput increases while reducing the

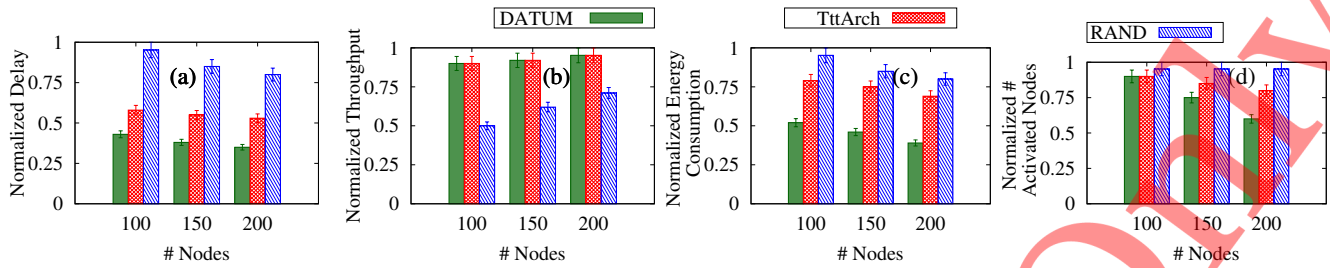


Fig. 4. Comparative analysis of DATUM, TttArch and RAND

network delay and the number of activated nodes in the network.

## VI. CONCLUSION

In this paper, we formulated a cooperation game theory-based dynamic topology control scheme, named DATUM, while ensuring high network lifetime and high QoS. Through cooperation, DATUM ensures that highly stable paths are chosen, which eventually ensures high network throughput with less network delay. Additionally, through simulation, we observed that DATUM ensures high network lifetime by reducing the number of activated nodes. Moreover, DATUM enhances the network lifetime by selecting the optimal communication range of activated nodes.

Future extension of this work includes understanding how the topology control can improve the performance of UWM-SNs in the presence of scalar underwater sensor nodes. This work also can be extended by revisiting the topology control scheme while considering the presence of underwater autonomous vehicles (AUVs).

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