Paper

Underwater Acoustic Sensor Node Scheduling using an Evolutionary Memetic Algorithm

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Abstract—Underwater Acoustic Sensor Networks (UWASNs) play an important role in monitoring the aqueous environment which has created a lot of interest for researchers and scientists. Utilization of underwater acoustic sensor node (UASN) scheduling for transmission remains, due to the limited acoustic bandwidth available, a challenge in such an environment. One of the methods to overcome this problem is to efficiently schedule UASN data using time division multiple access (TDMA) protocols the parallel transmissions, simultaneously avoiding interference. The paper shows how to optimize the utilization of acoustic sensor node bandwidth by maximizing the possible node transmissions in the TDMA frame and also by minimizing the node's turnaround wait time for its subsequent transmissions by using an evolutionary memetic algorithm (MA). The simulation of MA-TDMA proves that as the size of the network increases, every node in UWASN transmits with an average minimal turnaround transmission time. It also proves that as the TDMA cycle repeats, the overall network throughput gets maximized by increasing the possible node transmissions in the MA-TDMA frame.

Keywords—broadcast UASN scheduling, memetic algorithm, time division multiple access, underwater acoustic sensor network.

1. Introduction

Underwater Acoustic Sensor Networks (UWASNs) play an important role in weather monitoring and in the aqueous environment. Over a past few decades, underwater sensor nodes have been deployed for data collection performed manually, by recording [1]. This method of gathering information evoked much enthusiasm for the advancement of underwater sensor networks enabling the sensors to be connected. Acoustic communication is the most reliable and adaptable method in the case of the time-varying underwater channel [2]. The acoustic signal can be sent over longer distances (many kilometers), while electromagnetic waves are highly attenuated even over short distances, and they require using large aerials with high transmission power for communication [3]. On the other hand, optical links work well in underwater environments for short distance communication, but in large networks the data gets quickly absorbed and scattered [4].

Although acoustic communication eliminates the disadvantages of optical and electromagnetic signals in underwater environments, it suffers from limited bandwidth and large propagation delays due to the low speed of sound in water (approximately 1500 m/s) [5]. In general, UWASNs are one-hop and multi-hop networks that are directly based on hardware or are software-defined [6]. Every node within the network can communicate with its neighbor node directly, in the one-hop fashion. In a multi-hop network, all one-hop nodes collect and forward the data via an acoustic link.

In UWASNs, one of the important research area involves medium access control (MAC), which can provide efficient access to the shared underwater acoustic communication medium. Due to the large propagation delay in water, and also being half-duplex in nature for communication, terrestrial MAC protocols do not work effectively underwater [7]. There are two types of MAC protocols that are used for underwater communication. These are schedule based and non-schedule based protocols [8]. The existing non-schedule based protocols are like ALOHA [9], [10] and CSMA/CA [11]. Their implementation is simple, but they suffer from increased collisions at low data rates.

The schedule based protocols for UWASNs provide a high data rate with fewer collisions, and a good network throughput. The terrestrial sensor network protocols cannot be applied directly in UWASNs, due to the continuous change in the underwater environment [12]. In UWASNs, Time Division Multiple Access (TDMA) can work well for a prolonged period of time over which collision is been avoided efficiently [13]. The exact constraints in the underwater acoustic link can be solved using TDMA protocols [14]. TDMA is more appropriate for the underwater acoustic channel than FDMA and CDMA. FDMA and CDMA require more transmission capacity, which is not available in the underwater acoustic channel. In this paper we have considered fixed or anchored UWASNs for surveillance purposes, where each node has certain neighbors for communication. By using TDMA for scheduling, each node is assigned a different time slot for its transmission. It is to be noted that each node within the network takes a very long turnaround schedule for its next transmission. As the size of the network increases, time slots increase as well, which leads to a longer turnaround wait time for the transmission performed by individual nodes. This results in less effective utilization of acoustic bandwidth and low network throughput in big networks.

Underwater TDMA-based MAC protocols are introduced in [13], [15], [16]. All proposals have major issues in broadcast scheduling. In [17] hybrid spatial reuse TDMA (HSR-TDMA), the problem of broadcast scheduling has been solved using the hybrid spread spectrum method, but the hidden and exposed terminal issues have not been addressed effectively. The other drawback in HSR-TDMA is that few nodes in the network suffer from very long schedules for its subsequent transmissions, which directly affects the overall throughput. This broadcast scheduling problem can be addressed with evolutionary algorithms [18] to reach an optimal solution.

In this paper, the UASN broadcast scheduling problem experienced in applications that require frequent and periodic transmissions is solved by using the memetic algorithm. The aim is to minimize the node's turnaround transmission wait time and maximize the number of the node's possible transmissions in the TDMA frame that do not interfere within the same time slot, which results in full utilization of the acoustic channel limit available.

The remaining parts of this paper are arranged as follows. Section 2 explores underwater acoustic sensor node (UASN) for scheduling conflicts. Section 3 investigates the formation of the UASN broadcast scheduling problem. Section 4 describes the memetic algorithm used for solving the underwater broadcast scheduling problem. Section 5 reports the experimental simulation results and Section 6 draws the conclusions.

2. Underwater Acoustic Sensor Node Scheduling Conflicts

In multi-hop UWASNs, there are two types of major packet collisions that can occur in broadcast scheduling: primary collision and secondary collisions [19]. If node i and j start transmitting in the same time slot, then it will end up into a primary collision occurs. The secondary collision can occur, when node i in the network intends to receive two or more number of packets from the its directly linked acoustic nodes within the same time slot.

In underwater scheduling, in addition to primary and secondary conflicts, it is the non-trifling propagation delay that poses another serious problem. Because of the continuous change in water temperature, salinity, pressure, etc., the propagation delay may vary from time to time. In TDMA-based scheduling, the propagation delay can be avoided by considering guard interval time and the maximum expected propagation delay [20]. The primary and secondary collision can avoided in TDMA by considering node transmission performed in two or more hops [21].

Explanations are presented in [22] and [20], where guard time is added after every TDMA packet. MAC avoids packet collision early and delayed reception of the packet. The largest size of the expected propagation delay experienced underwater is reduced by using propagation estimation to stagger transmission [23]. HSR-TDMA presented in [17] overcomes the above conflicts and increases the number of node transmissions, but a few nodes within the network suffered from a long turnaround wait time for their subsequent transmissions. As the size of UWASN increases, the HSR-TDMA frame length also increases, which shows that a few nodes in the network suffer from very long turnaround times for their subsequent transmissions also, which means they will be the cause of the lowest successful packet transmission rate (STR) for those few nodes, which affects the overall network throughput [17]. Therefore, the main aim of this work is to develop an optimized TDMA schedule with an average minimum turnaround time for subsequent node transmissions, and to succeed in maximizing the overall UWASN throughput.

3. Formation of UASN Broadcast Scheduling Problem

UWASN is a special kind of an ad-hoc network that can be represented as an undirected graph $U(S,E)$ [17], where S holds the number of nodes comprising the network and E accounts for the link between nodes. Acoustic link $E(i,j)$ between nodes i and j shows that the two nodes are connected within the transmission range. Figure 1 presents a simple multi-hop acoustic sensor network referred to in [17]. Every node within the network is connected to its neighbor node to form a link.

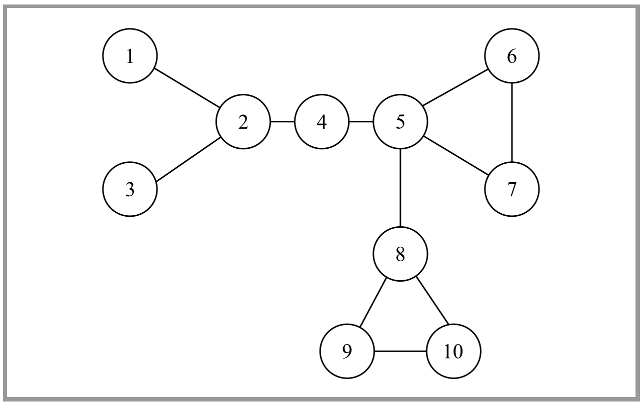

Fig. 1. A simple multi-hop UWASN.

The scheme from Fig. 1 has $|S| = 10$ network nodes in broadcasting. Primary conflicts are avoided by identifying adjacent node connections and secondary conflicts are eliminated by recognizing the nodes of two-hop connectivity. The identified connectivity matrix Con_M for the 10-node network is shown in Fig. 2. Rows in Con_M form the association between nodes. Columns represent sensor nodes. Zeros in Con_M indicate that there is no connection between nodes, while ones indicate that links exist. Two-hop connectivity for a given UWASN is considered to consti-

$$\text{Con\_M} = \begin{array}{c|cccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\ \hline 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 1 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \\ 7 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\ 8 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 1 \\ 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\ 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 \end{array}$$

Fig. 2. UWASN connectivity matrix.

$$\text{Hop\_M} = \begin{array}{c|cccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\ \hline 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 1 & 0 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 \\ 3 & 1 & 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 5 & 0 & 1 & 0 & 1 & 0 & 1 & 1 & 1 & 1 & 1 \\ 6 & 0 & 0 & 0 & 1 & 1 & 0 & 1 & 1 & 0 & 0 \\ 7 & 0 & 0 & 0 & 1 & 1 & 1 & 0 & 1 & 0 & 0 \\ 8 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 0 & 1 & 1 \\ 9 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 \\ 10 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \end{array}$$

Fig. 3. UWASN two-hop matrix.

tute a hop matrix Hop_M (Fig. 3). The rows of the two-hop matrix represent one- or two-hop connections between the nodes, while columns represent sensor nodes. The ones in Hop_M show that it might be one or two hops apart from the selected node.

The TDMA frame TDMA_M is shown as the $S \times T$ matrix, where T is the number of time slots in the TDMA frame and $S = \{S_1, S_2, \ldots, S_n\}$ represents the number of UASNs involved in the network shown in Figs. 4 and 5. The rows represent the number of time slots and all columns represent the transmitting nodes (i.e. adjacent nodes) in the network. The ones in the TDMA_M show that the nodes to transmit within that particular time slot without any conflicts and zeros are considered as receiving nodes in the network. Figure 4 represents a conventional TDMA frame for a 10-node network. Figure 5 shows an optimum MA-TDMA frame with minimum time slots and maximum possible transmission available for the same network. Nodes 1 and 5 are transmitted in the first slot, without any interference.

$$\text{TDMA\_M} = \begin{array}{c|cccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\ \hline 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 3 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 4 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 5 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 6 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 7 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 9 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 10 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{array}$$

Fig. 4. Conventional TDMA frame.

$$\text{TDMA\_M} = \begin{array}{c|cccccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 & 8 & 9 & 10 \\ \hline 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 2 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 0 \\ 3 & 0 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \\ 4 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 \\ 5 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \end{array}$$

Fig. 5. Optimal MA-TDMA frame.

The underwater TDMA scheduling issue has proven to be of the non-deterministic polynomial (NP) variety as presented in [19]. It is formulated as a special vertex coloring problem, whose solution for a given graph is NP-complete [24]. In this article, the problem is approached by adopting an evolutionary memetic algorithm. The optimum TDMA solution is determined based on the fitness criteria given by Eq. (1).

The available underwater bandwidth utilization is evaluated by Eqs. (2)–(3), and the average time delay for UWASN is calculated by Eq. (5). The tight lower bound $\Delta = 1$ terminates the algorithm. Let $Dg(s)$ be a set of UASN network connectivity, and let Max_D represent the highest degree of connectivity.

$$Max\_D = \max_{s \in S} |Dg(s)| \,. \tag{1}$$

Then the tight lower bound for MA-TDMA frame is created [21] as:

$$\Delta = |T| - Max\_D \geq 1 \,. \tag{2}$$

If $\Delta = 1$, the solution is optimal.

The acoustic bandwidth utilization is calculated for the entire UWASN:

$$\alpha = \frac{1}{|S|\,.\,|T|} \left[\sum_{i=1}^{|S|} \sum_{j=1}^{|T|} \text{TDMA\_M}_{\text{ij}} \right] . \tag{3}$$

For each node:

$$\alpha_s = \left[\sum_{i=1}^{|S|} \text{TDMA\_M}_{\text{is}} \right] . \tag{4}$$

The average time delay is calculated as:

$$\eta = \frac{|S|}{|T|} \sum_{i=1}^{T} \left[\frac{1}{\sum_{j=1}^{S} \text{TDMA\_M}_{\text{ij}}} \right] , \tag{5}$$

where η is the average node availability of UASN in the network. By minimizing the η value, the optimal optimum network design can be achieved [25].

4. Memetic Algorithm

Memetic algorithms (MAs) were developed from evolutionary algorithms that apply local search processes in the agents to improve their fitness [26]. MA belongs to the family of meta-heuristic methods and used the hybrid population approach which combines genetic algorithm and local search methods [27]. Adoption of MA successfully solves any difficult optimization problem. MA is used in computing to find the actual or nearby optimal solution. Algorithm 1 establishes the structure of MA to solve the problem of optimal TDMA node scheduling in underwater environments.

Algorithm 1: Memetic algorithm

```
Memetic algorithm (Mempop, maxgen, $Mem_s$, $Mem_c$, $Mem_m$)
Initialization
Generate initial population (Mempop)
MA operations
$Mem_s$ = select(Mempop)
while condition not terminated do
    $Mem_m$ = mutation($Mem_c$)
    $Mem_{opt}$ = optimizer($\alpha_s$, $Mem_m$)
    $Mem_{imp}$ = improver((Hop_M), $Mem_{opt}$)
    $Mem_{new}$ = evaluate($Mem_{imp}$)
    Mempop = survival(Mempop, $Mem_{new}$)
end while
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MA is based on the following inputs: the population for MA, maximum number of generations for the algorithm to terminate, probability measurement for the selection, crossover and mutation operations (Table 1). MA will iterate its process until any one of the following conditions is satisfied, either by achieving the tight lower bound $\Delta = 1$ or by reaching the maximum number of generations.

Table 1
Simulation parameters

Parameters	Values
Population size	60
Crossover rate	0.32
Mutation rate	0.01
Maximum generation	300

4.1. Selection and Survival Phase

The different probable conventional TDMA frames are chosen as MA population. The iteration process begins with the selection phase. The reproduction process is done by way of the k-tournament selection pressure. Depending upon the selection pressure, two parents are picked up from the mating pool for evolution. As per the *survival of the fittest* rule, only the fittest population would be retained for next generations by removing the unwanted population.

4.2. Crossover and Mutation Phase

The selected parents will go through the crossover and mutation process to produce a new generation. In this study a single point crossover is performed for each row, with random bit strings selected from the TDMA frame and with information interchanged between them. For example, consider two parents with single row P1 = 1111 and P2 = 0000, with a random crossover point as two. The produced children are C1 = 0011 and C2 = 1100. This child replaces the parents and checks for the constraints by referring to the Hop_M. If they violate the constraints, then it gets dropped from the process. The mutation phase is performed only at the rows of the TDMA frame obtained. It is done only by flipping the zeros to ones based on their non-violating condition. The mutation may increase utilization of the acoustic channel.

4.3. Optimizer Phase

In this phase MA tries to minimize the number of time slots in the TDMA frame. This process is performed by identifying the utilization factor α_s of each channel, based on Eq. (4). For example, if a node transmits more than once in the TDMA frame $(\alpha_s > 1)$, then this row is removed from the frame.

4.4. Improver Phase

This phase improves channel utilization by increasing the number of node transmissions by referring to the Hop_M. Since the optimizer and improver operation is carried out in each iteration of MA, the optimum TDMA frame is obtained in a lower number of generations, within an acceptable computation time. Fitness for the new population is evaluated based on two criteria: overall UWASN channel utilization factor and tight lower bound $\Delta = 1$. If both are satisfied, the algorithm gets terminated. In the worst case scenario, the nearby optimum solution is obtained by reaching the maximum number of generations specified in the algorithm.

5. Simulation Results for Underwater Broadcast Scheduling

Typical simulation results were obtained in Matlab using parameters shown in Table 1. Fitness is evaluated after every generation in the memetic algorithm. The UWASN is configured with 10, 50, 80, 100, 200, 300, 400 and 500 randomly located nodes, respectively. For a 10-node UWASN it is observed that existing HSR-TDMA node transmission

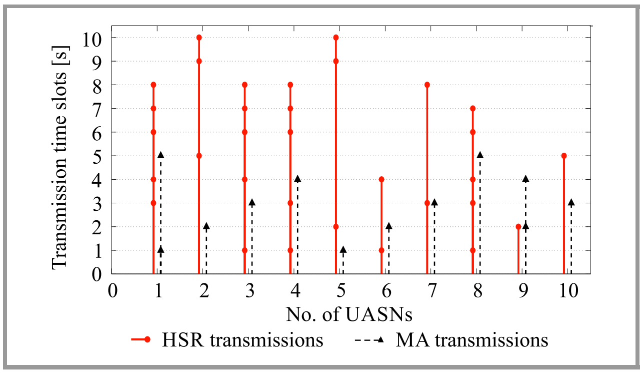

Fig. 6. Comparison between HSR and MA TDMA frame for 10 node UWASN.

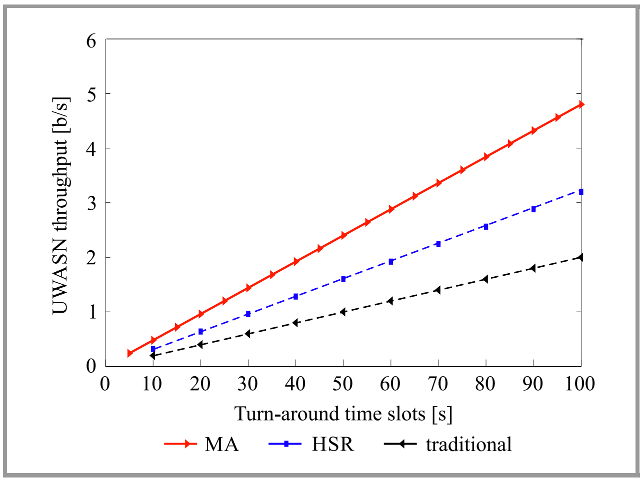

Fig. 7. Comparison of 10-node UWASN throughput.

Table 2
Comparison of MA-TDMA and HSR-TDMA frame length

No. of UASNs	No. of acoustic links	MA-TDMA frame length [bytes]	HSR-TDMA frame length [bytes]
10	22	5	10
25	43	7	25
50	98	9	50
100	200	11	100
250	430	12	250
500	1000	15	500

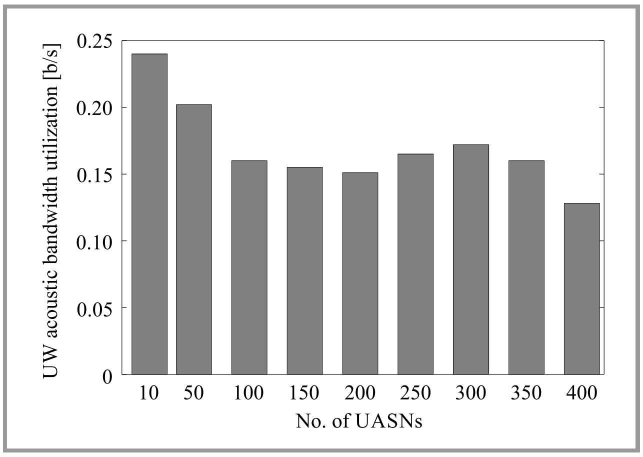

Fig. 8. Underwater acoustic bandwidth utilization for various network sizes.

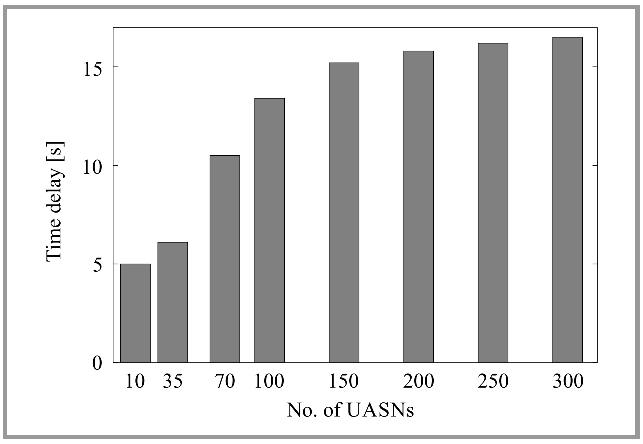

Fig. 9. Average time delay for different network sizes.

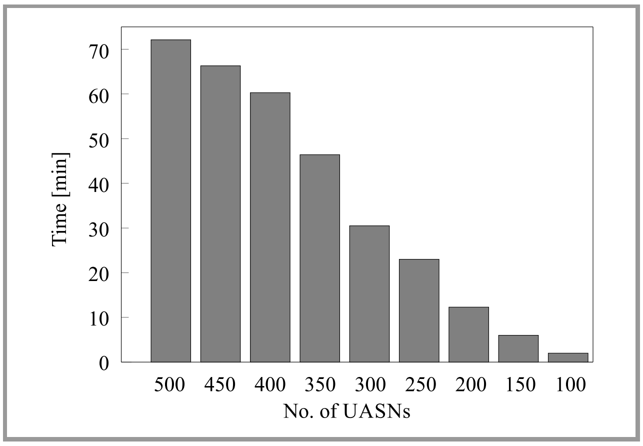

Fig. 10. Computation time take by MA for various network sizes.

takes place within 10 slots, for whereas MA-TDMA employs only five slots as shown in Fig. 6. Also, it can be seen in Fig. 6 that nodes 9 and 10 in HSR-TDMA have transmitted only once in time slot 2 and 5 respectively, which shows that it has to wait nine slots for their next transmission. This long turnaround wait time leads to the low successful packet transmission rate. Whereas in MA-TDMA, every node in the UWASN schedules with an average minimal turnaround wait time of five slots. This shows that the network throughput has increased along with the increase of the TDMA cycle, as shown in Fig. 7. Table 2 shows that as the number of nodes increases in UWASN, the HSR-TDMA frame length increases as well. Meanwhile, in MA-TDMA, the optimum frame length is maintained for various network sizes, which shows that MA-TDMA performs best as the network size increases.

Table 3
Simulation results of memetic algorithm

No. of UASNs	No. of acoustic links	Avg. ND	Max. ND	Optimal TDMA frame length	α	Avg. no. of generations	Computation time
10	22	4	4	5	0.245	2.3	1.3 s
50	84	4	6	7	0.202	5.10	7 s
80	150	7	9	10	0.175	7.48	11 s
100	200	7.5	10	11	0.160	16.5	2.0 min
200	400	8	10	11	0.151	30	12.3 min
300	600	7	10	11	0.172	54.3	30.5 min
400	800	12	16	17	0.160	60.28	65.3 min
500	1000	9	14	15	0.128	89.03	72.11 min

In the second stage, the MA process is performed 50 times. The average value of simulated results is shown in Table 3. The average node degree and maximum ND for various network sizes has been evaluated and the optimum TDMA frame was obtained. This optimum TDMA frame length is obtained by satisfying the tight lower bound $\Delta = 1$ of the MA. This proves that for various sizes of the network, the average turnaround time is maintained. It is also observed that nodes 1 and 9 in MA-TDMA, as shown in Fig. 6, have transmitted twice within 5 slots, which is a sign of better utilization of the acoustic bandwidth available. While comparing MA with traditional and HSR approaches, as seen in Fig. 7, one may observe that throughput for MA-TDMA was increased along with the increase of the TDMA frame cycle. Figures 8 and 9 show the utilization of bandwidth and the average time delay of UWASNs of various sizes, with the said parameters calculated from Eqs. (3) and (5). It can be observed that the average time delay increases as the size of network gets bigger. The channel utilization result obtained for various sizes of acoustic networks depends on the connectivity between nodes within the network. Figure 10 shows the computation time taken by MA for various sizes of UWASNs. As the number of nodes increases, the computation time taken by MA increases as well. Therefore, the simulation results for various simulation scenarios prove that MA-TDMA outperforms traditional and HSR-TDMA in turnaround transmission wait time and also produces high network throughput by utilizing the acoustic bandwidth available.

6. Conclusion

In this study, the UWASN TDMA frame has been optimized by using the memetic algorithm. The optimizer reduces the number of time slots in the TDMA frame which, in turn, reduces the turnaround transmission wait time in the network. The algorithm uses an improver that increases the number of possible transmissions in the frame, thereby increasing the effectiveness of utilization of the limited acoustic bandwidth available. MA-TDMA proves, even for large networks, that the average turnaround wait time for node transmission is very low when compared with traditional and HSR-TDMA. This proves that MA-TDMA increases network throughput, as the TDMA cycle gets increased. Compared to other evolutionary algorithms, MA provides an improved solution with an acceptable computation time. The simulation results prove that MA works well for UWASN broadcast node scheduling.

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