Scheduling Algorithms for Under Water Sensor Networks: Recent Approaches and Open Challenges

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Abstract. The research domain of UWSN (Under Water Sensor Networks) is gaining wide attention these days. The sensors are deployed on the sea surface or seabed for monitoring, data collection or surveillance purpose. Unlike terrestrial networks, the UWSNs use acoustic signals for data communication. The speed and bandwidth of acoustic signals is low compared to radio signals which are used in conventional terrestrial WSNs (Wireless Sensor Networks). As a result, protocol design in UWSN must be addressed separately than terrestrial networks. In this work, we have reviewed TDMA (Time Division Multiple Access) protocols for channel access. As TDMA is a collision-free method, it is preferred over other methods like random access methods or handshaking based medium access protocols. Some open issues are also proposed as follows: (i) It is found that very less or no work is done in the area of joint scheduling and topology formation for UWSNs. (ii) The problem of balancing schedule length of sink-rooted trees in multiple sinks UWSNs is also unattempted.

Keywords: Under Water Sensor Networks, TDMA Scheduling, Distributed Algorithms

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1 Introduction

Underwater Wireless Sensor Network (UWSN) is a special type of Wireless Sensor Networks(WSNs). In an UWSN, sensor nodes are deployed under water in a sea or river for different monitoring and surveillance applications. As mentioned in [4], their applications are environmental monitoring and oceanographic data collectison, tactical surveillance, assisted navigation and resource discovery. Unlike terrestrial WSNs, sensor nodes communicate using acoustic signals. The acoustic signals have very low propagation speed (1500 meters/second). The bandwidth of acoustic channel is also very low (i.e. less than 15KHz) [12, 31, 32, 3, 30, 29, 1, 2, 23, 28, 20]. Due to lesser attenuation, the acoustic signals rodriguez2012quality,rodriguez2016video travel greater distance than radio signals.

In literature, different MAC protocols for UWSN are proposed. They are (i) Handshaking based ([39],[18] and [9]) (ii) Random Access ([36],[7] and [22]) (iii) Scheduling based. As energy efficiency is important to achieve long network lifetime, handshaking based and random access based protocols are not desirable in WSNs . The Random Access protocols require the nodes to exchange special control packets (RTS/CTS) before transmitting data packet. This results in additional energy consumption. The Random Access protocols are contention-based. When network traffic is high [8, 24, 14, 35, 37, 21, 27, 26, 25], Random Access protocols will result in a large number of collisions. To recover from collisions, packets are to be retransmitted. As a result, additional energy is consumed. Thus the Handshaking based and Random Access protocols are not useful from an energy efficiency point of view.

The transceivers in acoustic modems have very high transmission power compared to terrestrial networks. So energy consumption is more. As it is difficult to replace or recharge batteries in an underwater environment, it is desired that network protocols should save as much energy as possible.

The scheduling algorithm assigns one (or more) time-slot(s) to every node for transmission. The slot assignment must be such that the slot in which the given node is receiving data packets from the sender, it should not overhear transmission from another sender at the same time. This is known as collision-free slot assignment ([34]). In [34], a review of distributed scheduling algorithms for terrestrial WSNs is given.

The scheduling algorithms of UWSNs are different than those of terrestrial WSNs. In terrestrial WSNs, the length of a time-slot is equal to the transmission time. This is because propagation delay is negligible due to high propagation speed of radio waves. But in UWSN, propagation delay is significant. So, the length of the time slot is the sum of transmission time and propagation delay. Thus to create a collision free schedule, location of every node and distance between the pair of sender and receiver should also be considered.

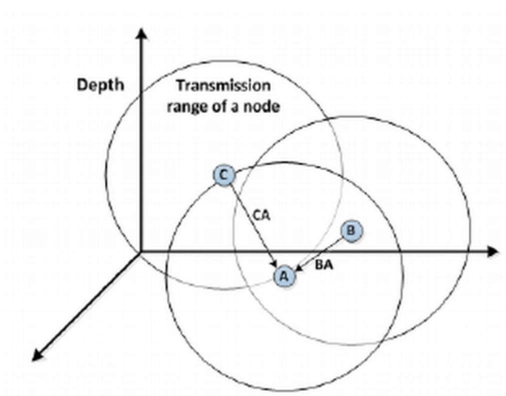

Figure 1: Transmission Range of nodes (taken from [4])

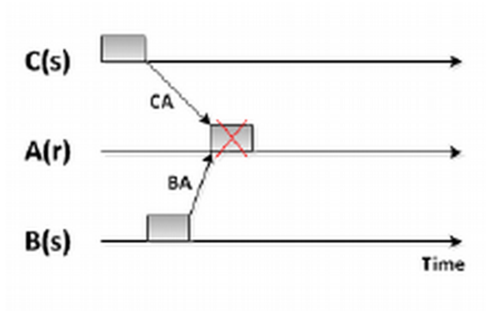

Figure 2: Spatio-temporal Problem: Collision does not occur at A (taken from [4])

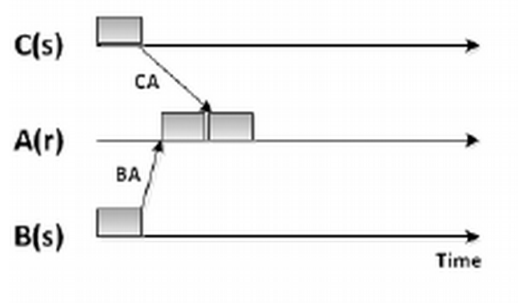

Figure 3: Spatio-temporal Problem: Collision occurs at A (taken from [4])

The propagation speed of acoustic signals depends on depth of water, salinity and temperature. As a result, the signals will suffer different propagation delays based on the location of sender-receiver nodes in the sea. So, a problem known as Spatial-temporal Uncertainty problem ([4]) occurs. It is explained in Figures 1, 2 and 3.

In Figure 1, node locations and their transmission ranges are shown. Here two nodes, B and C are transmitting packets to node A. As shown in Figure 2, even if they start transmission at different times, collision does occurs at A because their signals reach at the same time to A. But in Figure 3, even if nodes B and C start transmission at the same time, collision does not occur at A because their signals reach node A at different times.

Thus use of acoustic signals affect the design of Scheduling algorithms as these algorithms are aimed designing collsion-free schedule. In this paper, we have reviewed some recent scheduling algorithms for UWSN.

We could not find any paper similar to this one. The rest of the paper is organized as follows. In section 2, papers related to TDMA scheduling in UWSN are reviewed. In section 3, possible open issues are mentioned. The paper is concluded in section 4.

2 Related Work

In this section, review of some recent important TDMA protocols for UWSN is presented. In [4], a distributed MAC protocol known as EDMAC is proposed for UWSN. In this protocol, Every node selects a transmission slot based on its depth. Every node is equipped with a pressure gauge. So, the nodes are able to estimate their depth from the water surface. The network operation is divided into three phases: (1) Initialization (2) Slot selection (3) Data transfer.

During initialization, every node exchanges its ID and depth with neighbours. In the second phase, every node selects its time-slot(s). The slots selection progresses from bottom to the top. Every node runs a timer. The timer is inversely proportional to the depth of the node. The higher depth, the smaller the timer. The given node at depth d selects slot(s) only after its neighbours at depth (d+1) have selected the slots. After slot selection, normal data transfer using the selected slots takes place.

In [42], a sleep-wakeup scheduling algorithm is proposed. Node deployment in Underwater networks can be 2D (2 Dimensional) or 3D (3 Dimensional). In 2D deployment, nodes are deployed on the water surface. In 3D deployment, nodes are deployed below the water surface. In case of 3D deployment, node position is denoted by three coordinates: x, y and z. To form a topology, the area of deployment is considered as a big cube. The cube is divided into clusters. Each cluster is a set of 27 small cubes. Each small cube is known as a partition. Figure 4 illustrates the idea of cluster.

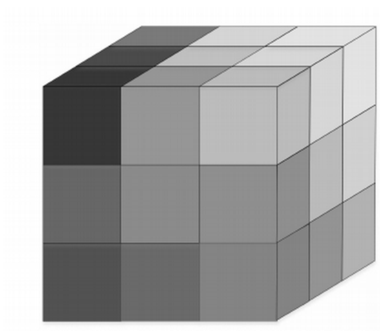

Figure 4: Concept of Cluster (taken from [42])

The highest energy node in the cluster is selected as cluster head. Each partition in the cluster may have a number of nodes. Within each partition, the highest energy node is selected as an active node by cluster head. The active node remains awake. It senses the environment and sends reading to the cluster head. The cluster head sends readings to the sink. The other nodes in the partition remain in sleep mode. After a certain time period, when the energy of the active node goes down, it is put into sleep mode and the other appropriate node becomes active. The role of cluster head is also rotated time to time.

The problem of sleep scheduling and slot assignment is handled in [38]. A variant of Genetic Algorithm (GA) is used to select minimal nodes to remain active such that maximum sensing coverage is possible. The active nodes sense the environment and send readings to the sink node. The inactive nodes will go to sleep state. They would not sense or transmit.

The chromosome is coded as follows: If there are total N nodes in the network, the chromosome is a vector a_1,a_2,a_3,.....,a_N. The value of a_i is 0 or 1. It is 0 if the node n_i is inactive, and 1 if it is active. The standard steps of GA like crossover and mutation are applied. The fitness function is such that the chromosomes having minimum number of nodes and maximum coverage survive. The proposed algorithm finds optimal solution using fewer generations than GA. To achieve this, it uses a technique known as Local Search. The details of the same are not presented here as it is not required.

Once active nodes are decided, nodes are divided into clusters. Each cluster-head assigns TDMA slots to its member nodes for collision free transmission.

In [15], it is considered that nodes are arranged in a chain topology like shown in Figure 5. The rightmost node is sink. The data transfer takes place starting from the left most node to the sink.

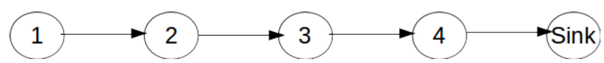

Figure 5: Chain Topology

The slot assignment is done considering following collision constraints: (1) When a node j is transmitting to node j+1 in time slot t, nodes j+2 or j-1 can not transmit in the same slot. (2) The node j-1 can not transmit in time slot (t+1) (3) The node j+1 can not transmit in slot (t-1).

In [5], Graph coloring is used to assign slots to nodes. The basic idea is that the colliding nodes are assigned different colors. The nodes with different colors use different time-slots. The proposed protocol is divided into three phases: Initialization, Coloring and Operation. In the Initialization phase, nodes broadcast beacon packets. Using beacon packets, every node learns about its two hop neighbourhood.

The next phase is coloring. The area covered by the nodes is considered as a collection of cubes. The width of each side of cube is 2 x T_r. Here T_r is the transmission range of nodes. Each cube is called a cluster. The node in the center of the cube is cluster head. The cluster head assigns different colors to its one hop neighbors. Each such one hop neighbor broadcasts its color. Thus two hop neighbors of the cluster head come to know about colors assigned to the one-hop neighbors. Now each two hop neighbor selects a color which is not selected by any of its one hop neighbor. Thus, interference within and across the clusters is prevented.

In [33], a Genetic Algorithm based approach for slot assignment is proposed. Assuming that the network has N nodes, the chromosome C is a vector of N elements. Each entry C[i] contains the slot number assigned to node i. The fitness function is such that the chromosomes resulting in the smallest TDMA frame go to the next generation.

In [16], the scheduling problem is modeled as Multi Vector Bin Packing problem (MVBP). There is a vector of slots. Each slot is modeled as a Bin. The sensor network is modeled as a graph. A vector C = C_1,C_2,...,C_N is found. Here C_i is a maximal clique. The items to be packed in bins are the sets or subsets of edges present in C. The objective is to fit all the edges in a minimum number of bins.

In [11], Combined Free Demand Assignment Multiple Access protocol with Systematic Round Robin Scheduling (CFDAMA-SRR) is proposed. It is an improvement over CFDAMA-RR [17]. The core idea of CFADAMA is as follows. The sink node is at the water surface. The sensor nodes are deployed within the water till the seabed. The sink node assigns time slots to sensor nodes.

The TDMA frame is divided into two types of slots: free slots and demand-based slots. Every node sends its request for a number of slots to the sink node. The sink stores requests in a request table. Then the sink assigns the required slots one by one to the requesting nodes by reading their entries from the request table. Such slots are called on demand slots. Still if there are some slots left in the frame, they are assigned to the remaining nodes. Such slots are known as free slots. The benefit is that nodes can send packets during free slots if a slot is not reserved in advance. Thus dynamic changes in the traffic can be accommodated. As slots are assigned one by one i.e. in Round Robin fashion, this is known as CFDAMA-RR.

The CFDAMA-SRR assigns slots in RR fashion to the nodes. But while assigning the free slots it gives priority to the nodes who are far from the sink. As in underwater networks, propagation delay is significant, the nodes far from the sink will have to wait for a long time to get transmission turn. So, if more free slots are allocated to such nodes, suddenly generated packets can be sent without waiting for longer.

In [10] a variant of CFDAMA is proposed, known as CFDAMA-IS (CFDAMA - Intermediate Scheduler). In default CFDAMA, the gateway or sink acts as scheduler i.e. assigns time slots to the sink nodes. The distance of nodes located at the seabed and the sink is very large, the request for time slots takes a long time to reach the sink. The same is the case with response coming from the sink. The nodes would get a faster response if the scheduler is near. So, the core idea behind CFDAMA-IS is to keep the scheduler at some depth such that it is at almost equal distance from all the nodes.

In [19], an attempt is made to implement TDMA without clock synchronization. Two different variants namely Transmit Delay Allocation MAC (TDA-MAC) and Accelerated TDA-MAC are proposed.

The working of TDA-MAC is as follows: The sink node exchanges a PING message with each node one by one. The sink sends PING request to a node. The node sends the PING reply back. So, the sink is able to calculate round trip propagation delay from itself to the node. It can also estimate individual delays in both the directions i.e. sink to node and node to sink.

Now sink sends a packet called Transmit Delay Instruction (TDI) to each node. Next sink broadcasts REQ (Request) packet in the network. Every node receives REQ packet, but at different time because of significant propagation delay. Upon receiving REQ packet, a node sends its data packet to the sink. But every node is informed through TDI about the time duration it has to wait before starting packet transmission after receiving REQ packet. Thus every node waits for a specific time duration and then sends its packet. This gives effect similar to TDMA. Once sink receives data packets from all the nodes, it sends REQ again. So, the next round of data transfer begins.

Due to very high propagation delays, TDA-MAC results in poor channel utilization. Data transmission can not begin until REQ reaches any one node. So, to increase channel utilization, in Accelerated TDA-MAC, sink broadcasts REQ packet before the current round ends i.e. the last few nodes send their data packets.

3 Summary of Related Work

We have reviewed various recent scheduling algorithms for UWSNs. Due to significant propagation delay in acoustic channels, scheduling in UWSN requires to be handled differently than the terrestrial sensor networks. In a terrestrial network, the scheduling algorithm depends on node density. But in case of UWSN, other factors like node position in water also affects the scheduling algorithm.

In Table 1, a summary of scheduling algorithms is given. Most of the algorithms have not considered any specific topology. It is explained in [40] that performance of scheduling algorithm depends on the topology. It is found that there is almost no work in the area of joint topology formation and scheduling for UWSN. One such work is presented for terrestrial networks in [6]. It is aimed at reducing the total schedule length of aggregated convergecast in tree based sensor networks. It is suggested that topology formation and scheduling must go hand in hand. The topology considered is tree. Every node should select its parent and slot at the same

Name of Paper	Core idea	Topology Formation addressed ? (Yes/No)
EDMAC [4]	Nodes select slot based on decreasing order of depth.	No.
Sleep wakeup scheduling [42]	Consider the area as a collection of clusters of cube shape.The cluster head selects the nodes who should remain wakeup based on energy of nodes.	Yes. Cluster based approach.
GA based approach [38]	The chromosome is a vector V of n elements if total n nodes are in the network. If V[i]=0, node has to sleep; to wakeup if V[i]=1. The fitness function is designed to minimize the number of awaken nodes and at the same time ensure full coverage.	Yes. Cluster based approach.
Optimal Scheduling [15]	Chain topology is considered. Slots are assigned such that collison does not occur.	No. It is assumed that nodes are arranged in a chain topology.
GCMAC (Graph Coloring MAC) [5]	The area of interest is divided into clusters. Each cluster is of cube shape. The cluster head assigns different colors to its one hop neighbours. The two hop neighbours of cluster head select colors independently.	Yes. Cluster based approach.
GA based approach [33]	The chromosome is a vector V of n elements if total n nodes are in the network. The value of V[i] is the slot number assigned to node i. The fitness function is designed to minimize the number of total slots used to schedule the entire network.	No.
Optimal Fair Scheduling [16]	The problem of scheduling is modeled as Multi Vector Bin Packing Problem. The network is modeled as a graph. Slots are modeled as Bins. The goal is to fit maximum number of objects (here edges) in the minimum number of bins.	No.
CFDAMA-RR [11]	Assign slots of a frame one by one (in Round Robin) to the nodes as per their demand. The free slots are assigned to the nodes who have not demanded slots.	No.
CFDAMA-SRR [17]	It is same as CFDAMA-RR. But nodes far from the sink are assigned more free slots so that they can send packets without much delay.	No.
CFDAMA-IS [10]	The idea is that scheduler node should not be at the water surface. It should be located such that all nodes are at equal distance from the scheduler.	No.
TDA-MAC [19]	TDMA is implemented without time synchronization between nodes.	No.

Table 1: Summary of Scheduling Algorithms

time.

The total schedule length will increase if a sequential approach is followed instead of joint approach. The sequential approach is a two step process. In the first step, topology is formed. In the second step, every node would select a time slot for transmission.

4 Problems and Open Challenges

It is mentioned in the previous section that there is no work addressing joint scheduling and tree formation in UWSNs. So, the first open problem is to design a joint scheduling and tree formation algorithm for UWSNs. As mentioned in [**?**], the scheduling should take place in bottom-up manner for aggregated convergecast. That is from leaf nodes towards the sink node. The parent node should select slots only after all its children have selected time slots. For raw convergecast, the scheduling should be top to bottom. The parent need not wait for the children to get scheduled. The parent can transmit its packet as soon as it is generated. So, one possible research work would be to design joint scheduling & tree formation algorithms for UWSNs dealing with raw convergecast and aggregated convergecast both.

The other possible research direction is to form sink-rooted trees in multi sink UWSNs such that the schedule lengths of trees are balanced. The main reason for using multiple sinks is that every node could send readings to the nearest sink and thus latency can be reduced. If there is a large network with a single sink, packets sent from the nodes far from the sink will face very high latency.

There are many papers utilizing multi-sink architectures, for example papers [41] to [13]. None of them have addressed the issue of schedule length balancing. The schedule length is the period after which every node gets its transmission turn. If one tree has a higher schedule length than the other tree, nodes of the first tree will wait for longer for transmission turn compared to the nodes of the tree with lower schedule length. Thus balancing schedule length is an important problem to handle. So, second possible research direction is to design joint scheduling & tree formation algorithms for multi-sink UWSNs such that schedule lengths of sink-rooted trees are balanced.

5 Conclusion

In this paper, some recently published papers addressing TDMA scheduling in UWSN are reviewed. After the review, some possible research directions are suggested as follows: (i) An attempt can be made to design a joint scheduling & tree formation algorithm for UWSN. (ii) The problem of schedule length balancing of sink-rooted trees in multiple sinks UWSN may be attempted.

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