# CFDAMA-IS: MAC Protocol for Underwater Acoustic Sensor Networks

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**Abstract.** This paper is concerned with coordinating underwater transmissions of acoustic sensor nodes. The use of acoustic waves to communicate underwater poses challenges to the functionality of Medium Access Control protocols. Long propagation delay and limited channel bandwidth are some of these challenges, which place severe constraints on the tradeoff between end-to-end delay and achievable channel utilisation. The Combined Free and Demand Assignment Multiple Access (CFDAMA) protocol is known to significantly enhance the delay/utilisation performance. However, CFDAMA will suffer from long round trip delays and inefficient utilisation of its frames if it is implemented in medium and deep water. The major contribution of this paper is a new approach, namely CFDAMA with Intermediate Scheduler (CFDAMA-IS), to efficiently use CFDAMA in underwater environments. The paper compares these two protocols in typical underwater scenarios. It is shown that the proposed approach significantly reduces mean end-to-end delay and enhances channel utilisation.

**Keywords:** Underwater Acoustic Networks · Medium Access Control

## 1 Introduction

Underwater Acoustic Networks (UANs) are the enabling technology for a wide range of applications. Monitoring of the underwater environment using sensor nodes is an example of particular interest in this paper. Figure 1 illustrates a typical example of a centralised UAN. The node placed near the sea surface is called a surface node, or gateway. It provides a high-speed connection to the terrestrial world. Sensor nodes are deployed at depth and called seabed nodes. Seabed nodes are designed to communicate acoustically with the gateway. Use of acoustic waves in underwater networks poses extreme challenges to the functionality of Medium Access Control (MAC) protocols. Long propagation delay

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and limited channel bandwidth are some of these challenges, which place constraints on striking a balance between network end-to-end delay and channel utilisation [3]. Contention-based MAC protocols are inefficient underwater [1]. Reservation-based protocols, for example, exhibit poor channel utilisation due to the long waiting time needed to establish an acoustic link underwater. Carrier Sense Multiple Access (CSMA) techniques also have poor delay/utilisation performance in UANs due to substantial guard intervals required to accurately sense channels with long and variable propagation delays [5]. Frequency Division Multiple Access (FDMA) [14] and Code Division Multiple Access (CDMA) [11] are less common compared with Time Division Multiple Access (TDMA). FDMA was tested in the Seaweb project [13]. The results were that inefficient use of the bandwidth and high vulnerability to multipath fading were reported. CDMA has some advantages over FDMA. It is not as susceptible to frequency-selective fading because each node can use the entire available bandwidth. However, in practice, the cost associated with these advantages is a decline in the data rate. Achieving low cross-correlation between codes in the underwater environment requires long codes. This would extensively reduce the effective data rates of UAN modems, typically operating at low data rates [15]. TDMA and TDMA-based protocols can easily adjust the number of orthogonal channels, and allocate variable data rates by just changing the number of time slots assigned to a particular node [5]. To improve deterministic schedule-based TDMA methods, contention-based and TDMA-based MAC protocols are combined [1]. They are classified as Adaptive TDMA where capacity is usually assigned on demand. In [3], the following three capacity assignment strategies were examined underwater. Demand Assignment is shown to have much greater tolerance to increasing channel load, but with longer delay. Free Assignment offers close to its theoretical minimum end-to-end delay, but only at only low channel loads. The Combined Free and Demand Assignment Multiple Access (CFDAMA) protocol combines the two latter protocols. CFDAMA is shown to minimise end-to-end delay and maximise channel utilisation, especially for densely populated long-range networks. However, CFDAMA suffers from long round trip delays due to the position of the surface node (the scheduler) that is placed almost site-depth above the seabed nodes. In other words, the distance between the scheduler and the seabed nodes is almost equal to the distance between the surface and the bottom of the underwater site where the network is deployed. This approach to implementing CFDAMA is to deterministically emulate the implementation of CFDAMA in geostationary satellite systems, for which CFDAMA is originally designed [8]. Moreover, the CFDAMA frames [3] are not utilised efficiently underwater. In the satellite scenario data packets need to be transmitted on the downlink frame [6]. This is not the case in the underwater scenario where all data packets are transmitted to the gateway.

The major contribution of this paper is a modification of CFDAMA, exploiting its advantages and overcoming its disadvantages in underwater scenarios. The new protocol is named CFDAMA with Intermediate Scheduler (CFDAMA-IS). The scheduler does not need to be at the surface node as it could operate at

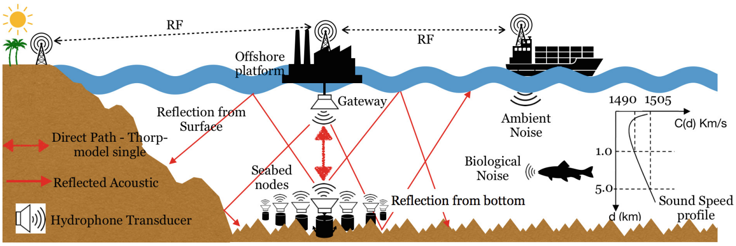



**Fig. 1.** Underwater acoustic network example

an additional intermediate node that can be placed anywhere near the seabed nodes to reduce round trip delays. This requires a change to the structure of the CFDAMA frames. The proposed approach significantly reduces the average round trip time required for making requests and receiving their acknowledgements and as a result, enhances overall delay/utilisation performance. Riverbed Modeller [4] was used in this paper to investigate CFDAMA-IS.

## 2 CFDAMA-IS Protocol

Detailed discussion on CFDAMA can be found in [3,7,9]. CFDAMA combines two capacity assignment strategies: free assignment and demand assignment. The major advantage of the CFDAMA protocol is that it exploits the contentionless nature of free assignment and the effectiveness of demand assignment in achieving high channel utilisation with a minimum end-to-end delay of only 1.5 surface hops. A surface hop is equivalent to a round trip from seabed nodes to the surface node. This combination can optimise the balance between the end-to-end delay and channel utilisation. However, when applied underwater, CFDAMA has two drawbacks:

- It will suffer from long round trip delays, proportional to the 1.5 surface hops, between the seabed nodes and their transmission coordinator since the scheduler operates at the surface node. Hence, locating the scheduler surface-to-bottom apart from its sensor nodes will extensively reduce CFDAMA performance in coordinating their transmissions.
- Utilising the CFDAMA downlink frame [6] without any adaptation to the underwater scenario will cause significant waste in the slots assigned to transmit data on the downlink frames.

The CFDAMA-IS scheme works in a more efficient way by minimising the round trip delay. The centralised scheduler, required by CFDAMA, does not need to be at the surface node to establish the communication links and coordinate transmissions of seabed nodes. In CFDAMA-IS, a node close to seabed nodes works as both a scheduler and a handover station to relay data packets to the gateway, used to act as the scheduler in the original CFDAMA [3]. CFDAMA-IS requires a change in the structure and use of the two CFDAMA frames to a more efficient exploitation as it is explained in the next section. As shown in Fig. 2 the time of a round trip was reduced significantly, and hence, the time needed to request capacity, receive its acknowledgement and transmit a packet is much less than one surface hop and a half. Other than that, CFDAMA-IS is implemented in a similar way as CFDAMA as explained in [3].

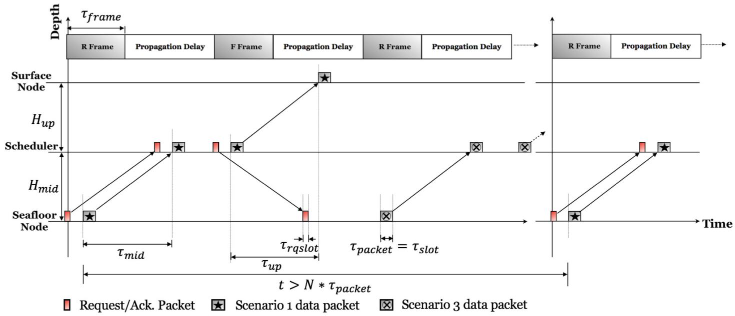



**Fig. 2.** CFDAMA-IS frame timing

## 2.1 CFDAMA-IS Frames Structure

Two frames are needed to implement CFDAMA-IS. As shown in Fig. 3, the forward frame (from the scheduler to the seabed nodes and to the surface node) and the return frame (from seabed nodes to the scheduler). Both frames are made up of two segments; a data slot segment plus either a segment of request slots in the case of return frame or a corresponding acknowledgement slot segment in the case of the forward frame. Date slots are allocated to nodes either as free assigned slots (F) or demand assigned slots (D). An appropriate request segment is inserted into the return frame for nodes to make capacity requests if needed. The forward frame is delayed with respect to the return frame by a period named the Forward Frame Delay to allow the request packets received in the return frame to be immediately processed and acknowledged with assignments in the forward frame. During the forward frame, the intermediate scheduler essentially does two jobs: sending acknowledgements of allocated slots to seabed nodes and successively relaying data packets to the gateway.

## 2.2 CFDAMA-IS Delay Analysis

The approach here is not to develop an exact CFDAMA-IS end-to-end delay model, but to develop a model that will incorporate those dominant factors which contribute significantly in determining the average end-to-end delay of packets. The delay caused by queuing was not involved here not only for simplicity but because of the fact that in scenarios with Poisson traffic and a relatively large number of nodes, queuing is not significant. Each successfully received packet

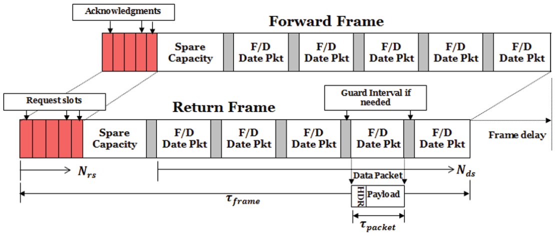



**Fig. 3.** CFDAMA-IS frame structures

must have gone through one of three possible scenarios. Scenario 1, in which packets get through by the use of free assigned slots. Scenario 2, in which a packet succeeds via a slot requested for a previous packet from the same node, and Scenario 3 in which a packet succeeds via a slot requested and granted for itself. Therefore, a packet's average end-to-end delay will depend on the scenario it experiences. Looking at the frames' timing depicted in Fig. 2 and considering the behaviour in Scenario 1, the mean end-to-end delay $E[D_{eted}]$ experienced by a packet arriving at an empty seabed node's queue is the combination of three terms:

$$E[D_{eted}] \approx \frac{N\tau_{slot}}{2} + 2\tau_{packet} + (\tau_{up} + \tau_{mid}) \tag{1}$$

The first term represents the average time a packet needs to wait until the next transmission slot, where $N$ is the number of seabed nodes and $\tau_{slot}$ is the data slot duration. The second term is related to the time needed for the packet transmission at the seabed node and the reception at the surface node which is dependent on the packet duration $\tau_{packet}$. The third term accounts for the aggregate propagation delay which comprises $\tau_{mid}$ (the time needed for a seabed packet to travel to/from the mid scheduler), and $\tau_{up}$ (the time needed to travel to the surface node). At high channel load values, nodes demand more capacity and therefore have to make a larger number of capacity requests more frequently. The protocol then will run with a much higher proportion of demand assigned slots (Scenario 3) causing an increase in the delay for packet transmissions. Incorporating the frame duration $\tau_{frame}$, the mean end-to-end delay of Scenario 3 can be expressed as follows:

$$\begin{aligned} E[D_{eted}] &\approx \frac{\tau_{frame}}{2} + 3\tau_{packet} + \tau_p \\ \tau_{frame} &= N_{ds}\tau_{slot} + N_{rs}\tau_{rqt.slot} \end{aligned} \tag{2}$$

$$\tau_p = \begin{cases} 3\tau_{mid} + \tau_{up}, & \text{CFDAMA-IS} \\ 3(\tau_{mid} + \tau_{up}), & \text{CFDAMA} \end{cases}$$

It is clear from Eq. (2) that the aggregate propagation delay $\tau_p$ that CFDAMA-IS experiences is $2\tau_{up}$ less than that of CFDAMA. This means that the demand assignment in CFDAMA-IS can handle capacity requests faster than it does in CFDAMA. Scenario 2 will dominate over the other two scenarios. Based on the state of the seabed nodes' queues, the average end-to-end delay will be gradually moving from its two extremes, i.e. the low extreme, which is experienced during Scenario 1 and the high extreme, which experienced during Scenario 3. Table 1 identifies the remainder of the parameters.

## 3 Simulation Scenarios

### 3.1 Underwater Acoustic Channel Using Riverbed Modeller

Riverbed Modeller (RM) [4] is a network protocol design and simulation tool, which has been used in this study to model the underwater acoustic channel. A number of its pipeline stages, shown in Fig. 4, have been modified to reflect underwater propagation mechanisms. The pipeline stages are primarily designed for the radio channel, but they can be customised to implement other types of wireless communication links. At least four stages, the shaded blocks in Fig. 4, had to be modified. For a large number of applications, the average speed of sound in water has been considered to be 1500 m/s [18]. The Thorp model [17] is commonly used to work out the absorption coefficient from which the total transmission loss is estimated as well as the received power. The undersea ambient noise is very often predicted using a set of empirical equations [16]. In this work, the modified pipeline stages are the propagation delay (stage 5), the background noise (stage 9), and the received power (stage 7) with accordance to the average speed of sound underwater, predicted underwater ambient noise using equations in [16], and estimated underwater received power using the Throp model. Based on these models RM calculates signal to noise ratio (SNR) and Bit Error Rate (BER) values. Depending on these BER values the receiver decides whether to accept or ignore a received packet.

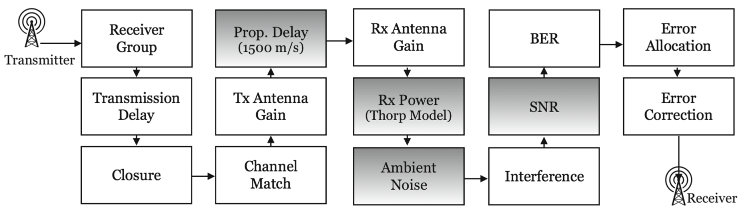



**Fig. 4.** Riverbed-based underwater acoustic channel

### 3.2 Network Topology and Data Traffic Model

The CFDAMA-IS specification does not need to assume any predefined information about the network topology or the number of nodes. The scheduling in CFDAMA is mainly based on the number of active nodes and propagation delays. Sensor nodes in the simulated network topology are distributed randomly, to cover an area of 500 m × 500 m. They are placed at two different depths 4 km and 500 m centrally below the IS node which is positioned above them at 500 m and 100 m depth respectively. The surface node is centralised above the coverage area. These two different depths are selected to reflect on the performance of CFDAMA-IS in two different underwater environments.

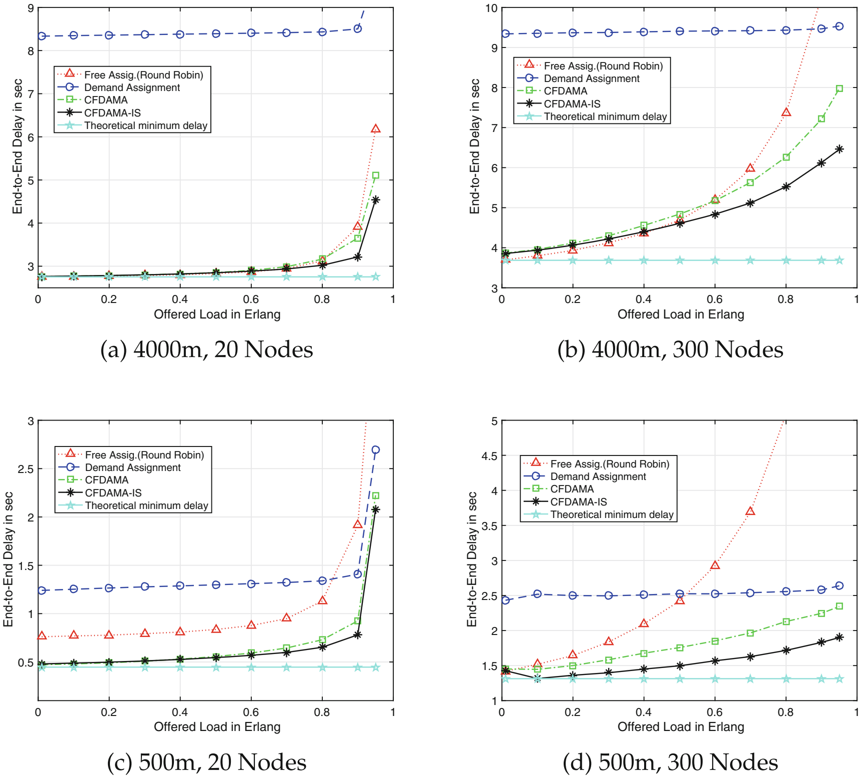
The Poisson model [2] is the traditional data traffic model in UANs. At every seabed node, packets are generated independently based on an exponentially distributed inter-arrival time. The mean inter-arrival time $\lambda$ for each traffic source is worked out with regard to the data carrying capacity of the channel using $\lambda = \frac{\tau_{frame}}{N_{ds}} \times \frac{N}{G}$. Offered load $G$ is measured in Erlangs [12]. The maximum channel utilisation is determined by observing when the end-to-end delay values reach a specific limit. The simulation parameters are listed in Table 1. These parameters are chosen to be within the range of operating parameters of current commercial modems, for example, the EvoLogics S2CR 15/27 modem [10].

**Table 1.** Simulation parameters

| Attribute | Value | Attribute | Value |
|---|---|---|---|
| $H_{up}$ (see Fig. 2) | 3.5 km and 400 m | $\tau_{slot}$ (date slot duration) | 6.6 ms (64 bit) |
| $H_{mid}$ (see Fig. 2) | 500 m and 100 m | $\tau_{rqslot}$ (req. slot duration) | 0.83 ms (8 bit) |
| $N$ (number of nodes) | 300 and 20 | $N_{ds}$ (number of data slots) | 32 |
| Bandwidth | 30 kHz | $N_{rs}$ (number of request slots) | 32 |
| Data rate | 9600 bps | G in Erlangs | 0.1–1 |

## 4 Results

Figure 5 (a)(b)(c)(d) shows the mean end-to-end delay against a variety of channel load ranging from 0.1 to 1 Erlangs. The graphs are for the four capacity assignment strategies: free assignment, demand assignment, CFDAMA and CFDAMA-IS, with a network of 20 and 300 nodes (sparse and dense networks). To reflect on two scenarios (deep and medium depths), Fig. 5(a)(b) show simulation results for the 4000 m-depth scenario whereas Fig. 5(c)(d) show the 500 m-depth scenario. With a large number of nodes - Fig. 5(b)(d) - it can be seen that the mean end-to-end delay of the Free assignment strategy grows significantly, for example, from 3.8 s *at* 1% channel load to 7.35 s *at* 95% channel load in the scenario with 4000 m sea depth. The reason behind this is the long period between successive transmission slots allocated to each node due to the large number of nodes. On the other hand, at low channel loads, the results indicate that the free assignment strategy can provide small end-to-end delay values, approaching the minimum delay limit optioned from Eq. (1). These results show that under the condition of Poisson traffic and a sparse network (low traffic), the free assignment scheme can perform reasonably well. The results in all the cases indicate that the delay performance of demand assignment scheme is generally dominated by the




(a) 4000m, 20 Nodes

(b) 4000m, 300 Nodes

(c) 500m, 20 Nodes

(d) 500m, 300 Nodes

**Fig. 5.** Delay/utilisation performances of CFDAMA-IS and the other 3 schemes

fundamental lower boundary of 1.5 surface hops (7.860 s for 4000 m depth and 0.93 s for 500 m depth). Interestingly, the scheme shows a much slower increase in the mean end-to-end delay values over virtually the entire channel loads than free assignment. This proves the ability of the demand assignment scheme to support much higher channel load levels owing to the dynamic allocation of the available capacity based on instantaneous node requirements. The results, nevertheless, show a significant difference in the mean end-to-end delay compared to the free assignment strategy in all cases. In the 300-node scenario, for example in Fig. 5(b), the mean end-to-end delay of demand assignment ranges from 9.3 s at 1% channel load to 9.5 s at 95% channel load, which is on average greater than the mean end-to-end delay of free assignment.

The results also show that the CFDAMA algorithm consistently outperforms its two constituent schemes in both mean end-to-end delay and channel utilisation. CFDAMA is inherently adaptive to the variation in channel conditions; it exploits the contention-less nature of free assignment and the effectiveness of demand assignment in achieving high channel utilisation efficiency. More importantly, the results indicate that the CFDAMA-IS protocol has a significant advantage over the other three strategies in terms of both end-to-end delay and channel utilisation. Comparing with the other three schemes, CFDAMA-IS experiences the lowest mean end-to-end delay throughout almost all channel loads and number of nodes shown in the figures in all scenarios. The minimum end-to-end delay that CFDAMA-IS experiences in each scenario is at very low traffic loads when the majority of the slots are freely assigned. At high channel loads, the end-to-end delay increases steadily, but still less than the minimum delay limit of the CFDAMA scheme and its two constituent schemes. For example, as shown in Fig. 5(b), at a channel utilisation of 1% of the channel capacity, the minimum end-to-end delay is only 3.8 s, which is less than the minimum delay of demand assignment. At the highest channel load of 95%, the mean end-to-end delay is still the lowest at 6.4 s.

## 5 Conclusion

This paper proposes a new form of the CFDAMA protocol underwater. Two major changes have been made to CFDAMA as follows: Firstly, the CFDAMA scheduling node was repositioned from being near the sea surface to just above the seabed nodes. This leads to minimisation of round trip delays between seabed nodes and the scheduler. Secondly, the CFDAMA forward frame is exploited not only for transmitting acknowledgements from the surface node to seabed nodes, but also for relaying data packets to the gateway. Simulation results have shown that the CFDAMA-IS protocol offers excellent performance in dealing with the trade-off between end-to-end delay and channel utilisation for Poisson data traffic through water. The major advantage of the CFDAMA-IS protocol is the fact that it efficiently combines the contention-less nature of free assignment and the effectiveness of demand assignment in achieving high channel utilisation. In CFDAMA-IS, the minimum demand assignment delay bound of 1.5 surface hops is overcome, which results in a significant enhancement in the overall delay/utilisation performance. For a vertical channel with data rate of 9600 bit/s and up to a 4000 m depth/range with Poisson traffic offered by 20 and 300 nodes, CFDAMA-IS makes it possible to load the channel up to 95% of its capacity with a delay performance that is better than that of CFDAMA and far superior to the demand assignment scheme and more bounded than the free assignment scheme.

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