A Novel Architecture for Multi-hops Routing Ad Hoc Underwater Acoustic Sensor Networking

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Underwater acoustic communication ad-hoc networks are an innovative issue, which faces difficult medium problems, such as long propagation time and dynamic network topology. In addition, due to high error probabilities typical for this channel it is preferred to use collision free mechanism. Because of the long propagation time, protocols such as MACA, requiring transmissions of pre-messages, achieve relatively low network efficiency. Moreover, TDMA scheme do not utilize the network resources allowing reuse in the code domain (using CDMA) and spatial reuse when possible. In this paper we introduce an underwater acoustic ad-hoc network consist of multi-hop relays and supports quality of service such as network reliability, minimum latency and priority. The network concept is based on CDMA confronting the acoustic underwater network challenges, such as the "near-far" problem and fast time varying topology. Using this concept, a sea trial including broadcast, multicast and unicast transmissions of SMS and navigation messages was carried out in various scenarios including multi-hops near the shores of Israel. We present results from this sea trial demonstrating the efficacy of the proposed networking scheme.

1 Introduction

There are various different approaches for the design of underwater communication networks. The differences between the approaches is in choosing the communication protocol [2], matching it to the characteristics of the underwater channel, the various types of data packets that are transmitted in the network and in the quality criteria upon which the network's efficiency is measured. We define the Channel's throughput as the time duration to send a data packet compared to the average time required to handle a data packet. Thus communication algorithms that include collisions, such as Aloha and Slotted-Aloha, shall achieve low throughput in an underwater channel characterized by a long propagation delay, mainly because of the need for retransmission [3]. On the other hand, protocols that are collision avoidance based, such as CSMA and MACA [3], also do not achieve high throughput, since they are based upon a time period of waiting between transmissions, which is proportionate to the duration of the data packet propagation (CSMA) or a virtual carrier sense mechanism (MACA) [3], taking valuable channel time, due to the long time periods of propagation in underwater channels. Moreover, these protocols are used mainly for unicast messages where in our case are less common.

In this paper we present a few problems of the Underwater Acoustic Channel (UWAC), which derive from the characteristics of the underwater channel, we also present a realization of an ad-hoc underwater communication network that facing these problems. The communication network which we discuss is a network designed for a small amount of users, with mobile network nodes, so that the network topology changes quickly, in comparison to the rate of the data packet's transmission. In addition, we present design for protected distribution of packets, and an ability to perform network relays. We also present results of an oceanic experiment, held across the Haifa shore, which demonstrates the network's performance.

2 Challenges of implementing network communication over UWAC

The propagation delay for a data packet in the UWAC is 200 times bigger than the propagation delay in a RF channel. In addition, the information transfer rate in the channel is very low [2]. These delays lead to relatively long data packets (because of the need to include the propagation delay within the data packet's duration). As a result, the network throughput might be very low. Therefore, there is an acute need of economizing the amount of data packets going through the network. The overhead for transference of network data (topology, acknowledgements, etc) regarding the network's status is high.

Another issue of the UWAC derives from interferences of the channel, which lead to high error probabilities and low detection probabilities. The network's performance is damaged because of the significant multi-path effect of the UWAC [4] and because of the low signal to noise ratio, deriving from the spreading and absorption losses in the channel [5]. Therefore, the reliability of proper data packet transference in the UWAC is not high, and there is a high chance of losing data packets in the channel. This phenomenon makes it necessary to use message End-to-End guaranteed delivery protocols. These protocols enable tracking data packets transferred within the network and ensuring its proper delivery to the destination nodes.

The characteristics of the near-far phenomenon might also occur when the UWAC is not symmetrical, that is, when the signal to noise ratio for the data packets transmitted in the channel from one node to the other is not symmetrical. In such a case, the connectivity matrix between the nodes is not symmetrical and the transmission of the virtual carrier sense messages between the nodes (such as CTS-RTS) is significantly damaged.

When there is need to relay the data packets in the network, the problems mentioned above worsen. The duration of data packets transmission is doubled, as well as the probability of data packets errors. In addition, the topology of the channel, which changes relatively quickly, makes it harder to stabilize the network in adaptive networks protocols, such as MACA, because of the need to receive CTS messages before each data packet transmission, which takes a long period of time, while in fact the structure of the network's connectivity might have already been changed.

3 Typical requirements from network transmissions in UWAC

In order to explain the reader the motivation for realizing the network presented here, the following paragraph shall specify the requirements from the network. In this paper we discuss a network that has a small amount of nodes, distributed randomly across an oceanic space, which includes barriers that lead to a loss of acoustic line of sight.

The network should produce a reliable data packet transmission between all the network's nodes. Therefore, the network's protocol must contain an ability to relay data packets between different nodes. In addition, the data packets transmitted in the network might be unicast - a data packet designated for a single node, multicast - a data packet designated for several nodes or broadcast - a data packet designated for distribution to all the nodes in the network. Our network includes an ability to send a data packet for a specific destination or to several destination nodes, while informing the rest of the nodes in the network (same as Carbon Copy 'CC' in email).

As stated before, there is a requirement for a robust End-to-End guaranteed delivery mechanism. This mechanism enables tracking the status of the transmitted data packet using acknowledgment messages from the destination nodes and from nodes which are solely for notifying. In case there was a failure to receive the data packet at its destination, the message will be sent again. The relay ability also requires a relay ability of the aforementioned acknowledgment messages.

In this paper, we deal with user data packets of two kinds navigation messages that contain datum-point information regarding the node, and text messages which contain unrestricted information, in SMS configuration. In addition there will also be relayed navigation messages and relayed SMS. The various kinds of data packet require a realization of a prioritization mechanism between the data packets sent through the network. We shall make transmission and relay of text messages a higher priority than control data packets, and make sending self messages a higher priority than relaying messages from other nodes.

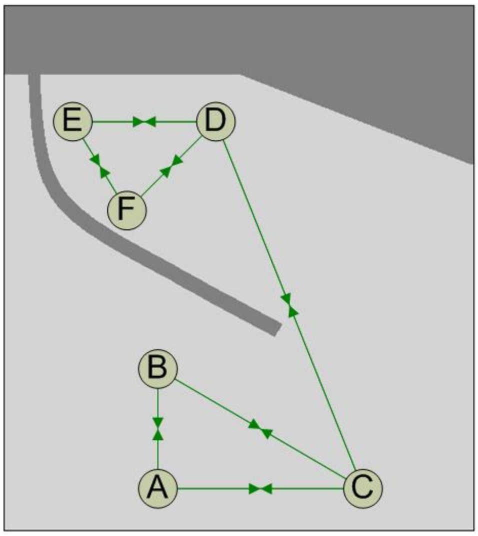

Fig.1 A demonstration of a higher throughput possibility in the communication network.

The requirements from the network and the problems of the communication channel with which the network must deal, require a development of robust network protocols. These protocols require being based upon static mechanisms that are not dependant upon the network's structure. On the other hand, static network mechanisms lead to a communication network with low channel throughput, because of a partial usage of the network's resources such as spatial diversity and CDMA. An example for this can be seen in Fig.1 where A and B are not connected directly to E and F (and vice versa) and therefore the channel's throughput can be better if these two pairs of nodes shall run separately (similar to cluster formations [6]).

The content we see in front of us, should first of all answer the robust requirements of the network. This requirement, as we see it, is the biggest challenge of the UWAC. The content of the network that shall be presented shall therefore try to answer this aforementioned tradeoff, by being based upon a grooved structure for the channel, that is, allocating slots in time for different nodes, but giving priorities to different nodes dynamically. In the next paragraphs we shall present two optional realizations of the network. The presentation of the realizations shall be accompanied with specifying the advantages and disadvantages of each realization, in order to give the reader a better perspective for his content considerations, which we considered while developing this content. In the next paragraph we shall present two network protocols.

4 Network protocol, TDMA based

Since the requirement for the data packets distribution reliability and the robustness of the network are our main concern, protocol based upon TDMA (Time Division Multiple Access) is the natural choice. Although this algorithm achieves a low channel throughput, it prevents many problems such as collisions and near-far problem.

The TDMA scheme allocates a transmission slot for every node in the network, in which only one node is allowed to transmit. The time period required to complete a round in which all nodes transmitted is called frame duration. We assume that all the network's nodes are synced, up to a certain level. We will further discuss the network abilities such as the relay of data packets, prioritization of data packets and End-to-End guaranteed delivery.

4.1 Relay protocol

The underwater network nodes are not necessarily directly connected. The distances of the nodes beyond the maximal transmission range, physical blockage, blockage caused by a lack of symmetry in the channel and the movement of the nodes cause the network topology to be asymmetrical and dynamic. Therefore, relay in the network cannot be made in a pre-defined manner, and so, the connectivity list of each node is disseminated at a high rate. The proactive approach of the connectivity list dissemination is chosen to decrease the latency in the network with high rate of application messages where most of them are broadcast type. This transmission of information ensures that every node could make a dynamic picture of the network topology, which changes in time.

The relay is made in an ad-hoc fashion. For each receiving data packet the receiving node decides whether the destination node of the received data packet is connected to the current node, but isn't connected to the packet's node source. For example, let us consider the network in Fig.1. Node A transmits a data packet to node D, which is received in node B and C. Upon receiving the data packet from node A, node C shall direct the data packet to node D, after an examination of the network topology, as it is reflected in node C, which shows that node A is not on the connectivity list of D, but node C is on that list.

The decision whether to relay a message is made only in relation of the connectivity list of the data packet destination node, regardless of the connectivity list of the origin of the data packet. Therefore, it can be understood, that the origin of the data packet cannot choose the direction of the data packet relay. The motivation for this content derives from the asymmetrical nature of the underwater channel and from the dynamic network topology.

4.2 Priority queuing of data packets and prioritized nodes

Because of the long propagation delay and the relatively low rate of information in which the data is transferred in the channel, there is a substantial limit on the number of data packets that a node is allowed to transmit in its transmission window. Therefore, advanced priority queuing mechanism to handle data packet priority was developed. The guide line for this mechanism is prioritization of original data packets upon relay data packets, and also of SMS messages upon navigation messages. This mechanism is realized in the DLC layer.

Each node accumulates transmission data packets in three different FIFO queues: original text data packets relay text data packets and relay navigation messages. The structure of the three priority queues also enables to control the rate of information transmitted in the channel, by limiting the lines depths. In this manner, there is a diminishing of starving of data packets, which is common in networks with a large amount of data packets (such as navigation messages).

A priori information regarding the network's topology might lead to a requirement for nodes with higher transmission priority than other nodes. For example, in Fig.1 , most of the network's data packets are transmitted by nodes C and D. therefore, a larger slot can be given to these nodes.

4.3 End-to-End guaranteed delivery mechanism

The low level of reliability in the underwater communication network [5] requires a realization of a distribution protection mechanism. This mechanism tracks the status of outgoing data packets, and enables an additional automatic transmission of the data packet, in case there is a failure in its transmission. The End-to-End guaranteed delivery mechanism requires transmission of automatic acknowledgment messages from the destination nodes of the data packet.

The End-to-End guaranteed delivery mechanism is performed in the transport layer, by transmitting the acknowledgment information as piggiback over the navigation messages, which is periodically transmitted in the channel. Thus, the transmission and relay of the acknowledgments is executed as part of the relaying of the navigation messages, which contain the node connectivity list, and is not a separate data packet.

The mechanism is realized by two FIFO queues with the ability to remove messages from the queue at any moment. A message transmitted from a certain node enters such a queue, along with the list of nodes that are the data packet's destinations. When the data packet reaches the end of the queue, it is transmitted again in the channel, and enters into an additional queue of End-to-End guaranteed delivery. When the packet also reaches the end of this queue as well, an indication of failure is given. When an indication of acknowledgment is received from a certain node, the confirming node is deleted from the list of the data packet destination nodes. If all required acknowledgments arrived, the data packet is removed from the queue it is in.

The rate of progress of the End-to-End guaranteed delivery queues is dependent upon the communication regime of the channel. The formation of TDMA dictates a progress rate of once in every transmission cycle for every node, since acknowledgment from different nodes can only be receive once in a transmission cycle.

5 Description of a network sea trial

In order to check the performances of the network a sea trial was executed. The sea trial was performed along the Israeli coastline, in an environment which enables testing the network's performance in situations where not all the nodes in the net are directly connected. The trial included 3 and 4 nodes, which were placed in 6 different locations. The maximal distance between the nodes was 3 km, and the depth was between 4 to 10 meters. The trial was performed under problematic conditions, which included harbor noises, substantial multi-path effect (because of the low depth of the water), concealment and dynamic network topology. Fig.2 presents the experiment's scenarios in a schematic manner.

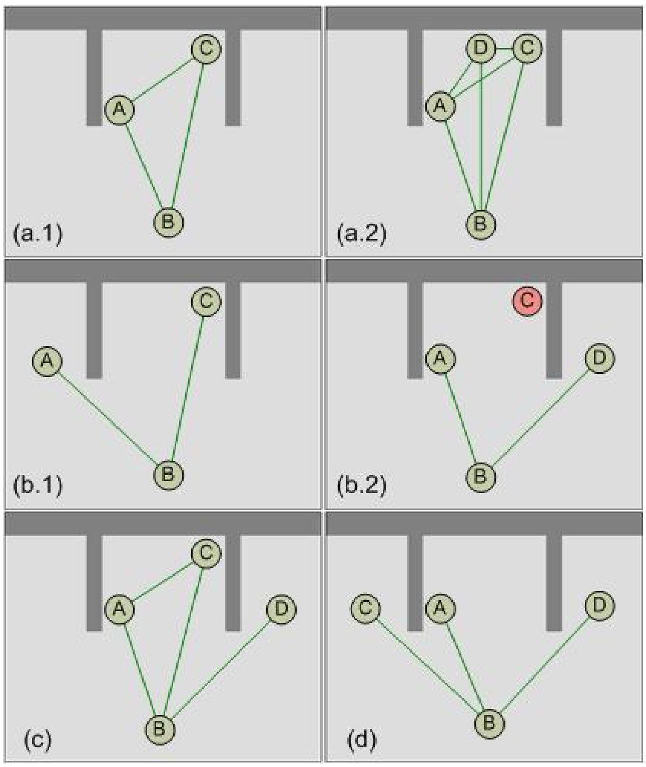

Fig.2 Scenarios of an oceanic network experiment

The six scenarios described in Fig.2 contain a description of the network between 3 nodes (scenarios a.1 and b.1) and between 4 nodes (scenarios a.2, b.2, c and d). The trial included scenarios with direct connectivity between the nodes (scenarios a.1 and a.2), scenarios of relaying 2 nodes by a single node (scenarios b.1 and b.2) and scenarios that include a more massive relay by a prioritized node (node B in scenarios c and d) with slot duration of 1.5 times than regular time slot. During the trial, both navigation and SMS messages were transmitted by all the network nodes.

In order to calculate the performance of the network, we chose a quality criterion of the Channel Latency which is the time difference between the data packet transmission and the reception of the packet acknowledgment by the transmitted node. We denote the *Channel Latency* as T_{pd}^{msg}. It is clear that the network's efficiency is better when T_{pd}^{msg} is small. The performance of the network is evaluated while taking in mind the delays created in the relay nodes, the channel's dynamic topology and the prioritizing of the data packets.

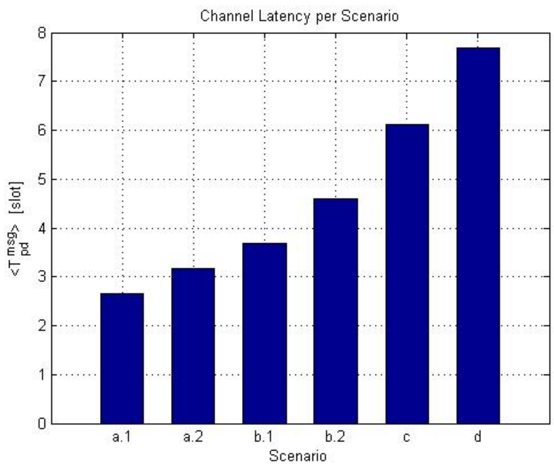

Fig.3 The average time period of handling each data packet for all scenarios

In Fig.3, the average T_{pd}^{msg} is presented, for each of the six scenarios described in Fig.2. As the amount of relayed data packets rises, T_{pd}^{msg} rises as well. For example, in scenario b.1, about 0.7 of the data packets are relayed compared to 0.85 in scenario c. The rise of T_{pd}^{msg} value occurs since more data packets and acknowledgments of delivery should have gone through a double path in the network.

In addition, the results show that when the number of data packets rises, the value of T_{pd}^{msg} rises as well. An example can be seen while comparing the average T_{pd}^{msg} value between scenario c, which contains a node that relays between two groups of nodes, and between scenario d, which contains a node which relays 3 groups of nodes. When a single node (B, in both aforementioned examples) has a great load of data packets to relay, several data packets to be relayed which were received in this node shall be postponed to the next slot, because of the priority mechanism, and they shall be detained a complete frame duration, in addition to the delay caused by the relay itself.

The results of the sea trial, presented in Fig.3 show that when the network consist of a significant amount of relays, the duration of T_{pd}^{msg} increases by up to 2.5 times than a situation where no relays were executed in the network (for example, scenario d, compared to scenario a.2). This result occurred even when a longer transmission slot was allocated for the relaying node, by defining it to be a preferred node. This hindrance in the performance worsens when the number of relays in the network rises (for example, scenario a.2 compared to scenario a.1).

6 CDMA-TDMA based MAC protocol

In the preceding paragraph we presented the problem of the network's throughput in TDMA scheme, as it was demonstrated in a sea trial. In this paragraph we offer a collision free solution for raising the network throughput in multi-relay scenarios.

The offered MAC protocol is based on the spatial reuse idea, while combining dynamic TDMA scheme with CDMA. The protocol is based upon the observation that in any given moment there is only a single node which is allowed to transmit in the TDMA scheme, while there could be situations in which we can enable several nodes to transmit simultaneously. For example, in Fig.1, nodes A and E can transmit in the same slot without mutual interference. In addition, because of the CDMA mechanism, nodes A and D can also transmit in the same slot, if there is no near-far problem in the network. Therefore, we shall aspire to identify in each slot, which are the nodes besides the node that was allocated for the current slot that can transmit, in this very slot, without interrupting each other.

The suggested protocol is based upon TDMA scheme, with an attribution of every node to a designated slot, a priori. This a priori attribution ensures minimal rate for each node avoiding the phenomenon of node starvation. Any other node not designated to the current slot, examines whether it can join transmission in this slot. The examination is made according to the connectivity matrix, which is built dynamically at every node, and according to a weighting mechanism, partly dynamic and partly static. It is also possible to insert elements of prioritization of nodes into the weighting mechanism, by raising the weight of the node a priori (preferred node) or according to the number of nodes that the node is directly connected to.

In order to illustrate the aforementioned protocol, let us assume a scenario such as illustrated in Fig.1, and that node A in this scenario is the designated node to the current slot. Nodes B and C shall not transmit in the current slot, because of the direct connectivity between them and node A. Also, since most of the application messages are broadcast, only one node out of nodes D, E and F can transmit in the current slot, since transmission of two of these nodes shall lead to a collision. Nodes D, E and F make an ad hoc decision, according to the weighting mechanism. The adaptive element of the aforementioned weighting mechanism enables control of the data stream in the net although the network topology is time varying. Thus, if we assume, for example, that node D is chosen in the slot designated to node A, in the slot designated to node B another node shall be chosen (E or F). The weighting mechanism enables also diminishing the near-far problem, which might be caused, when nodes A and D transmit simultaneously. An example for such a process over the scenario illustrated in Fig.1 is described in Fig.4.

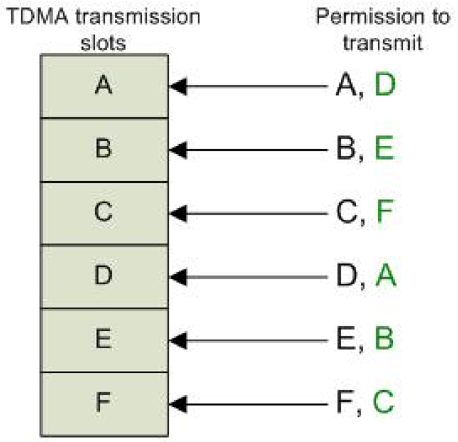

Fig.4 The average time period of handling each data packet for all scenarios

The example presented in Fig.4 shows that the number of nodes transmitting in a single slot is two times larger than in a classic TDMA regime. Raising the number of nodes transmitting in each slot, decrease by two the T_{pd}^{msg} value and the network's throughput increases, without defecting the communication reliability.

7 Conclusion

In this paper we presented architecture for an underwater communication network, TDMA based. This architecture include multi-hop relays and quality of service such as End-to-End guaranteed delivery, message prioritization and minimization of channel latency in network which faces transmission of large amount of broadcast messages.

The network was designed to cope with the underwater acoustic channel challenges, such as near-far problem, dynamic topology, long time periods of delay, high error probability and more. On the basis of this protocol an ad hoc communication network was realized, and its performance was examined in a sea trial that included multicast, broadcast and unicast transmissions, for SMS messages and navigation messages, in scenarios that included relays and End-to-End guaranteed delivery of data packets. The results of this sea trial proved the network's ability to cope with the challenges of the underwater channel, yet showed that the network's throughput diminishes as the number of relays in the network rises, and in situations in which the load of relays is concentrated in single nodes.

In order to increase the channel utilization, another MAC protocol was offered, based upon TDMA and CDMA schemes, which enables transmissions of several nodes simultaneously. Thus, gaining a significant rise in the channel's throughput, in situations that the classic TDMA shows poor performance.

Acknowledgments

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