Study of MAC Protocols for a Real Underwater Sensor Network Application

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Abstract—Simulations have proven to be useful in aiding the research in wireless and underwater sensor networks. Simulations can be very convenient also when planning the development and deployment of an underwater sensor network for a real application. However, in order to achieve trustworthy results and to be able to extract correct conclusions, accurate models and real parameters should be used.

This paper studies the behaviour of different medium access techniques when they are applied to a real monitoring application. To this end, different MACs where implemented and tested by means of simulation, using accurate models fed with real data.

Keywords: Simulation, Protocol analysis, Low-power design, MAC protocols, Sensor networks.

1. Introduction

Underwater sensor networks have many interesting and challenging applications like submarine surveillance or environmental monitoring. These applications, and specially the long-term ones, have to be carefully planned before the actual deployment of sensor nodes.

Carefully planning the necessary hardware and algorithms that are going to be executed can avoid node or even network failures once the application is already deployed. This is very important, since retrieving the already deployed nodes can be very expensive and sometimes even impossible.

Simulations are a very convenient way of testing algorithms and protocols before their actual deployment. However, one has to be certain that the simulation results are as much accurate as possible. The use of, for example, a too much simple physical model or supposing synchronization among all nodes, can alter the behaviour of the protocol and sometimes lead to wrong or incomplete conclusions [1].

In this paper we aim to give some insights on which medium access protocol might be more appropriate to apply on a given application. This application is enclosed under a Spanish research project of an unattended monitoring installation in an offshore fish farming facility. The hardware that is going to be employed in this application is a low-cost, low-power modem with wake-up capabilities and limited computational resources [2]. This forbids us from using complex medium access protocols which would need higher computational power.

In order to carry out this study, a model of the actual hardware modem for the ns-3 simulator is employed [3]. Moreover, since the simulations accuracy is a major requirement, they are performed using the existing Bellhop propagation model for the ns-3 simulator. In addition, Sound Speed Profile (SSP) and bathymetry data where extracted from the location where the application is going to be deployed by using the WOSS API [4].

The rest of the paper is organized as follows: Section 2 introduces the target application of this study. Section 3 highlights some of the more interesting medium access protocols for our application. Section 4 discusses the selected protocols for this study and Section 5 shows their implementation. Finally, Section 6 analyzes the simulation results and in Section 7 conclusions and future work are drawn.

2. Target Application

The target application of this study is enclosed under a Spanish research project of an unattended monitoring installation in an offshore fish farming facility. The general architecture is depicted in Figure 1, where different sensor nodes are placed at fish nets and to the sea bottom also. These nodes are capable of measuring different environmental variables on demand and send these data to the sink.

Sink nodes (there might be more than one sink node depending on the installation requirements) are placed at buoys at the sea surface and equipped with solar energy-harvesting capabilities. They also include some radio modem in order to communicate with an onshore installation.

A sink might require a group of nodes to send some environmental variables periodically during a certain amount of time. In order to keep the architecture as flexible as possible, there is no need for these nodes to be known a priori. For example, the sink can send a message asking for certain information and the desired sample
frequency. After that, the nodes capable of providing this information have to compete to acquire the channel and send the information.

Finally, regarding the underwater communication capabilities, all nodes are equipped with a low-power, low-cost underwater acoustic modem with integrated wake-up capabilities presented by Sanchez et al. in [2].

The aim of this paper is to give insights on which medium access protocol might be more adequate to implement for this application. While bearing in mind the application constrains, the wake-up capabilities of the underwater modem and the fact that it has to be implemented in a low-cost micro-controller with limited computational performance. To this end, in the following section several well known medium access control protocols are going to be introduced.

3. Related work on MAC protocols

Medium Access Control (MAC) protocols are mainly in charge of avoiding packet collisions but, generally speaking, they have to deal also with other factors like, energy efficiency, scalability or latency. These protocols can be divided into two main groups, contention-free and contention-based.

Among the contention-free MAC protocols, time division, frequency division and code division are the three basic types.

In Time Division Multiple Access (TDMA), each node is assigned a fixed slot for it to transmit hence, all nodes must be synchronized in time. Moreover, time guards must be included in order to take into account the propagation delay and the synchronization accuracy [5].

Frequency Division Multiple Access (FDMA) divides the available bandwidth into different frequency bands, allowing different nodes to transmit and receive at the same time while avoiding collisions. In underwater acoustic networks, this scheme is considered unsuitable due to the narrow bandwidth available for communications [6].

Finally, the last basic type of contention-free protocols is the Code Division Multiple Access (CDMA). These type of protocols use binary codes to modulate the signal using a spread-spectrum technique, allowing different nodes to communicate at the same time using different codes. The drawback of using this technique comes with the reduced data rates due to the generally long codes needed to achieve low cross-correlation [7].

On the other hand, contention-based MAC protocols avoid the pre-allocation of resources by allowing the nodes to compete with each other and obtain the medium access on demand. This group of protocols, usually relay on a random access to distribute transmissions and normally they also include some recovery mechanism in case a collision occurs. Two well known and basic protocols in this group are ALOHA and CSMA.

In order to improve efficiency over these simple protocols, different authors have proposed numerous ones which, although maintaining the random access mechanism, perform a channel reservation before sending the actual data packet.

Multiple Access Collision Avoidance (MACA) [8] and its adaptation to underwater acoustic networks MACA-U [9] are well-known protocols that can be classified in this group. Nodes using these protocols perform a handshake exchanging RTS and CTS packets prior to the actual data transmission. Although they can avoid some collisions, they are not data collision-free protocols and some data packets might be lost.

A different proposal is the Propagation-delay-tolerant Collision Avoidance Protocol (PCAP) [10], which also performs a RTS/CTS handshake, but deferring the CTS packet transmission so that it reaches the data transmitter after twice the maximum propagation delay. The major disadvantage is that the protocol needs all nodes to be synchronized.

Another random access with reservation protocol is the Distance-aware Collision Avoidance Protocol (DACAP), proposed in [11]. This protocol tries to avoid Data-RTS collisions by deferring the data transmission for \( t \) seconds after sending the RTS. It also introduces a short warning packet sent by the receiver if it overhears an RTS after sending a CTS. The main drawback of this protocol is that the time \( t \) has to be set up in advanced and cannot be adapted to network changes.

One more approach is the one given by the original FAMA (Floor Acquisition Multiple Access) protocol [12], which prevents packet collisions provided that the RTS and CTS frames are long enough. Given the long propagation delay of the underwater acoustic medium, these packet lengths might be very long, hence Molins et. al. propose in [13] the Slotted FAMA MAC protocol. This protocol provides some energy savings since nodes do not have to transmit long RTS/CTS frames. However in this case, the slot length needs to be equal to the maximum propagation delay plus the transmission time of a CTS
packet, which can lead to a low channel utilization and also requires synchronization among all nodes.

Finally, T-Lohi (Tone-Lohi), a hybrid between RTS/CTS and CSMA, is proposed in [14]. This protocol adapts automatically the contention time to the number of contending nodes. The nodes send a short packet called tone prior to the actual data packet to count the number of terminals contending for the channel. If a node does not receive any other tones, it starts the transmission. However, if it receives more tones, it adapts its backoff time depending on the number of tones received.

4. Chosen Protocols

Given the application constrains where the underwater nodes have to remain operative and unattended during large periods of time and the network load is not periodically and uniformly distributed, TDMA was discarded from this study. Moreover, the use of any sort of time slots for transmitting data would imply time synchronization, which would increment the energy communication costs and increase its complexity.

The FDMA alternative was also abandoned due to the reduced bandwidth of the hardware modem (1 KHz) and the fact that previous empirical experiments discarded it too [15].

CDMA, although promising, requires more computational power than the one that the implemented node can provide. Moreover, the employed modem can achieve a transmission speed of 1 Kbps and implementing CDMA would decrease this speed considerably [7].

From the other studied protocols in the previous section, PCAP also requires synchronization among all nodes. DACAP, although interesting, needs a fixed parameter to be set up before deployment and given the changing topology of the network (the number of contending nodes might vary depending on what parameters is asking the sink for), it seemed unsuitable for this application.

ALOHA and MACA-like protocols are the ones that seemed more appropriate since they do not need time synchronization and, using the backoff mechanism, can adapt to the number of contending nodes. Although very interesting, the implementation and study of T-Lohi is left for future work.

For these reasons, ALOHA-CS, MACA and FAMA are the protocols implemented and studied in this work. These protocols have been adapted, when possible, to take advantage of the modem wake-up capabilities.

5. Protocol implementation

In order to evaluate these protocols, they have been implemented under the ns-3 simulator [16], using the model of the underwater modem with wake-up capabilities, previously presented in [3].

The wake-up system has two operational modes, a tone mode and a pattern mode. When configured to use a tone mode, the wake-up subsystem wakes-up the main receiving circuitry whenever a tone is present in the channel. Hence, when using this mode, a node sends a wake-up tone prior to the actual packet and all nodes within the receiving distance would wake-up and receive the packet.

When using the pattern mode, a node only wakes-up when it receives a predefined pattern (which can be the node address). Following the same procedure, the transmitter sends a wake-up pattern prior to the actual packet but only the intended receiver will receive this packet.

This wake-up subsystem also allows to assess the channel state continuously without waking up the main radio circuitry.

In what follows, we introduce how the different protocols have been adapted to use the underwater wake-up modem model and implemented under the ns-3 simulator. Mainly, each time the MAC layer needs to send a packet, a wake-up signal is sent first, so the receiving nodes can wake-up their main radios and receive the packet.

5.1 ALOHA-CS

This protocol is the most simple one of the implemented protocols in this work. Each time there is a packet to be sent, the protocol asserts the channel and, if it is free, it begins the transmission. If the channel is busy, it waits and backs-off for some predefined amount of time when it starts the procedure again. The packets are kept in a FIFO queue until they are sent.

The same protocol was implemented also but including acknowledgements. In this case, the packets are kept in the FIFO queue until the acknowledgement is correctly received.

5.2 MACA-like protocol

Before sending the actual data packet, a RTS/CTS exchange is done between sender and receiver. These packets include the estimated amount of time that will take the complete communication. This time is estimated by knowing the maximum propagation time and the length of the data packets being sent.

Like the previous one, packets are kept in a FIFO queue and a second version of the protocol has been implemented including acknowledgements.

5.3 FAMA-like protocol

Like the previous one, before sending the data packet, a RTS/CTS exchange is done between sender and receiver. As specified by the FAMA protocol, these packets
Table 1: Underwater modem energy consumption

<table>
<thead>
<tr>
<th>MODE</th>
<th>Wake-up Modem</th>
<th>Modem</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX mode</td>
<td>120 mW</td>
<td>120 mW</td>
</tr>
<tr>
<td>RX mode</td>
<td>8.1 µW</td>
<td>24 mW</td>
</tr>
<tr>
<td>IDLE mode</td>
<td>8.1 µW</td>
<td>24 mW</td>
</tr>
<tr>
<td>SLEEP mode</td>
<td>-</td>
<td>3 µW</td>
</tr>
</tbody>
</table>

have to be of a specific length in order to avoid data packets colliding with other packets.

The FAMA protocol is designed in a way that all nodes must remain awake listening the channel and updating their timers.

In order to take full advantage of the wake-up capabilities, the node will remain in a low-power state until a packet is directly sent to it. Instead of listening the channel continuously through the main radio, it takes advantage of the carrier sensing capabilities of the wake-up modem, updating the timers accordingly to the channel state.

This protocol implementation also includes a FIFO queue and a second version with acknowledgements. Moreover, following the original specifications, a burst mode is supported where, once the node has acquired the channel it can send more than one data packet.

6. Simulation Results

In order to conduct the experiments, we implemented the previous protocols using the ns-3 simulator and adapting them, when possible, to make use of the underwater modem wake-up capabilities.

The Bellhop model was fed with the SSP and bathymetry data, obtained using the WOSS API [4], from the coast of Burriana (Spain) where the application is going to be deployed.

The modem consumption parameters were the ones shown in Table 1 and the transmission speed was set to 1000 bps [2].

An scenario of 100x100 meters was tested with 10, 50 and 100 nodes randomly deployed. Only one sink was placed at the center of the scenario. Each scenario was simulated several times in order to achieve a confidence interval of ±1 with a confidence level of 95%.

All simulations where seeded using the number 1330703057 and each repetition was done advancing the run number [16].

The simulation stop time was set to 30 minutes.

All traffic was directed to the sink node and was generated by a Poisson distribution with an average packet inter-arrival time of 0.6 seconds, which assured that the network was working under saturation. Each packet was generated by this function and assigned to a source node using a random uniform distribution.

In order to obtain the best possible results for each protocol regardless of the backoff algorithm used, a set of simulations was performs for each protocol varying the backoff time from 0.5 seconds to 20 seconds and the best results in terms of packet delivery ratio are the ones shown in the following figures.

In what follows the results of the simulations are going to be introduced for each one of the implemented protocols using and not using acknowledgements.
6.1 Without acknowledgement

Figure 2(a) depicts the number of correctly received packets by the sink normalized to the theoretical maximum. As can be seen, ALOHA-CS is the one that achieves the maximum throughput followed by FAMA x2, which is FAMA but sending two data packets instead of one.

The MACA learn protocol is exactly the same as the MACA-like implemented protocol but using the wake-up tone instead of the pattern mode. This way, all nodes can learn about the ongoing transmissions and try to avoid collisions. The MACA-like protocol achieves slightly higher packet delivery ratios than the remaining two.

When taking a look to the power consumption in Figure 2(b), one can see how the wake-up tone use of the MACA learn protocol highly increases the energy consumption of the nodes since they wake-up for almost every transmission done.

It can be seen also how ALOHA-CS has a huge energy consumption per each correctly received packet. On the other hand, the remaining three protocols have a similar energy consumption, being FAMA x2 the lowest one.

Focusing on the sink energy consumption as depicted in Figure 2(c), ALOHA-CS is the protocol that achieves the lowest one because the sink does not have the CTS sending overload.

6.2 With acknowledgement

When acknowledgements come into play, the difference in the number of correctly received packets is greatly reduced between ALOHA-CS and FAMA x2, as shown in Figure 3(a).

Figure 3(b) shows how the lowest energy consumption is achieved by FAMA x2, except for the 100 nodes scenario where the ALOHA-CS consumption is a bit lower. Regarding the other protocols MACA learn has the highest energy consumption since it uses the wake-up tone mode.

Finally, sink energy consumption per data packet is depicted in Figure 3(c) and as expected, since ALOHA-CS does not have the CTS overhead it has the lowest energy consumption. FAMA and FAMA x2 have a stable energy consumption, independently of the number of nodes, which might be useful when trying to implement energy-neutral operations at the sink node.

7. Conclusions

This paper studies the suitability of different MAC protocols to a real underwater sensor network application. To this end, we study different MAC proposals and, bearing in mind the hardware characteristics and restrictions, we have implemented and tested them under the ns-3 simulator.

In order to achieve as accurate simulations as possible, we have used real SSP and bathymetry data from the location where the application is going to be deployed, as well as, real energy consumptions measured from the actual hardware. Moreover, accurate models like the Bellhop propagation model and the modem model where used.

Future work will include the study of more MAC protocols like T-Lohi and real tests at the actual offshore installation using real hardware nodes.
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References


