Modelling and Simulation of Underwater Low-Power Wake-Up Systems

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Abstract. Underwater Wireless Sensor Networks (UWSN) have become an important area of research due to its many possible applications. One example are the long-term monitoring applications were the nodes only need to be awake during a small fraction of time. This kind of applications can greatly benefit from low-power, wake-up systems. However, despite the fact that the simulations can greatly improve the development time of new algorithms and features, optimizing their performance, up until today there is no wake-up system model available.

In this paper a low-power underwater wake-up model for the ns-3 simulator is going to be presented. Using this model the, as far as we know, only two available underwater modems with integrated wake-up capabilities are compared in terms of energy consumption.

Keywords: Underwater modems, energy-efficiency, wake-up, modelling, simulation.

1 Introduction

Underwater Wireless Sensor Networks (UWSN) have become an important area of research due to its wide range of applications, ranging from submarine surveillance to monitoring of the marine environment. Recent advances [3] have made feasible to develop relatively large underwater networks although the deployment and maintenance costs are still high. Hence, there is still a need for low-cost, low-power modems capable of extending the nodes' battery life as much as possible.

This is usually the case of long-term monitoring applications, were the nodes only need to be awake during a small fraction of time and remain in the sleep state for most of the time. To that end, underwater low duty-cycle MAC protocols have been develop in order to allow the nodes to remain in the sleep state as much as possible and implement some degree of synchronization to maintain the connectivity of the network.

These approaches usually maintain a permanently and rotative awake backbone to assure the connectivity of the network at all times or periodically wake-up the nodes so they can hear for transmissions intended for them.

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This solutions, although very interesting, maintain some nodes awake during periods of time where no data transmission is being made.

Nowadays acoustic modem design allows the implementation of a low-power reception state where nodes keep listening the channel with very low power consumption (much lower than the regular reception state), while the not necessary circuitry remains in sleep state [17], [10]. This way, the modem is able to listen and recognize certain stimuli sent prior to the actual data packet and wake-up the main circuitry to receive it. In [4] the authors present a study where the viability in terms of energy-efficiency of this solutions is shown.

Since the deployment costs of this networks is very high, simulations are an essential tool to test and tune new features and algorithms before their implementation with real hardware. However, to the best of our knowledge, there is no underwater wake-up model available.

In this paper a low-power underwater wake-up model for the ns-3 simulator [7] is going to be introduced. Using this model the, as far as we know, only two available underwater modems with integrated wake-up capabilities are going to be compared in terms of energy consumption.

The remaining of this paper is organized as follows, in Section 2 the more relevant MAC protocols based on the previously introduced sleep-cycle solutions are introduced. In Section 3 the main features and energy consumption characteristics of the available underwater wake-up modems will be presented. Section 4 introduces the proposed underwater wake-up model for the ns-3 simulator. Section 5 describes our simulations and obtained results. Finally, in Section 6 conclusions are drawn and future work in this line is highlighted.

2 Related Work

The design of energy efficient and reliable communication protocols has been one of the main research focus in radio-frequency (RF) sensor networks and in underwater wireless sensor networks. The key aspect in order to accomplish this, is to design a medium access protocol (MAC) that is able to achieve good packet delivery ratios while consuming as less energy as possible.

In order to prolong the battery life, different methods can be employed from the medium access perspective. One of them is to reduce the packet signalling overhead and lower the number of collisions. Another one is to switch off the radio transceiver when the node does not need to send or receive any data. However, by doing so, the node is totally disconnected from the network and can no longer act as a relay node if needed.

There are different approaches on how to disconnect this nodes and bring them back online. The Geographic Adaptive Fidelity (GAF) [19] achieves this by dividing the sensor network into small grids in such a way that at each point in time only one node in the grid can be in active mode, while the others have their radios disconnected. This protocol, originally developed for RF networks might be difficult to apply underwater, since it needs some location information and partial synchronization between the nodes. Moreover, it relays on dense networks, which might be difficult to achieve underwater, due to the high node and deployment costs.

Span [2] is another protocol developed originally for RF networks, which selects a limited set of nodes to form a backbone where the packets can be forwarded at all times. To form this backbone, the protocol needs to interact with the routing layer. The other nodes can transition to sleep states more frequently since the do not have to relay any data. Moreover, in order to distribute the energy consumption, the nodes are rotated in their backbone role. The performance of this algorithm is very density-dependant so it might be difficult to achieve high energy savings in an underwater environment.

The protocol called STEM (Sparse Topology and Energy Management) [14] takes a different approach than the other two previously introduced. While GAF and Span try to always maintain a path for the packets to be forwarded without inquiring in long packet delays, STEM trades off this latency for energy savings. To do so, all nodes are in a low duty-cycle sleep state and when a sender wants to transmit, it first send a beacon in such a way that it is guaranteed to be received by the receiver in some bounded time. When the receiver wakes up and hears the beacon it informs the sender and gets prepared to receive the data. Although the authors claim that it is not necessary, the results in [14] are obtained under the assumption that there are two radio transceivers available, with the associated extra cost and consumption, one for the actual data transmission and one for the transmission and reception of the beacon signals.

Although they can be applied underwater, this protocols where specifically design for RF networks. Given the harsh underwater environment and the different transmission characteristics [3], there has been some effort from the scientific community in order to design new protocols for the underwater environment.

Since in the underwater acoustic environment the cost of transmitting one data packet is much higher than the cost of receiving it, in [20] the authors analyze the effect, form the energy-efficiency point of view, of using low duty-cycle protocols in the underwater networks. They show that a simple duty-cycle scheme, coupled with some power control can reduce the overall energy spent in the network.

R-MAC [18] is one of this low duty-cycle protocols specifically designed for underwater networks. In this protocol each node periodically transits between the listen and sleep states. The duration of this states is the same for all nodes and each one randomly selects when to perform this transition. After each node estimates the latency to all its neighbours it starts broadcasting its own schedule and learning the others, until all the nodes in the network have the information from all their neighbours. After this configuration phase the nodes can start to transition between their wake-up and sleep states and to send their data. In order to send data packets, the sender have to agree with the receiver on when to do this transmission and it has to be done during a reserved period of time called R-windows. The protocol does need to re-run its configuration phase so nodes can synchronise again and this can be very energy consuming depending on the actual time they need to perform the configuration.

Another low duty-cycle protocol specifically design for underwater networks is the UWAN-MAC [8]. This protocol sets up some sort of adaptive TDMA (Time Division Multiple Access [15]) where each node broadcasts when is it going to send its data and learns the schedule of the others in order to wake-up for the transmissions on which it is acting as the receiver. After that, on each data transmission the node piggybacks when is going to be the next transmission. This way, the receiver can adapt to the new schedule. This protocol assumes that the clock drift is not significant and that the sound speed will remain constant between the schedule updates.

In this kind of protocols, where nodes have to partially synchronise themselves in order to be able to achieve a good operation, the studies some times fail to quantify the cost of the network reconfiguration and the clock drifts might have in the overall performance and energy consumption. As an example, Casari et al. analyze in [1] how fast the network performance drops for increasing synchronization drifts when using the UWAN-MAC protocol.

Another approach for the nodes to efficiently transition between the wake-up and sleep states comes with the introduction of a low-power, wake-up modem. This wake-up system consumes very low energy while it remains on the reception state so, a node can turn off its main radio and remain listening on this low-power radio waiting to receive a transmission.

In [4] the authors analyze the situations in which a low-power, wake-up modem can save energy compared to idle-time sleep cycling algorithms. They show that, in fact, wake-up modems can outperform the sleep cycling solutions and even behave almost as well as the ideal sleep cycle where nodes magically wake-up exactly at the same time when they have to receive a packet.

In the following sections, the currently available low-power, wake-up modems are going to be introduced and compared using the proposed underwater low-power, wake-up system model for the ns-3 simulator.

3 Low-Power, Wake-Up Modems

To the best of our knowledge, currently there are two proposed modems with an integrated wake-up system: the Wills underwater modem [17] and the ITACA modem [11], [10], [12].

3.1 Wills Underwater Modem

Wills underwater modem is a low-power acoustic modem designed for small range networks [17]. It includes a dedicated wake-up tone receiver and a Mica mote for the packet processing and coding, this motes consume when activated $24mW$[5]. Its communication distance ranges from $50m$ up to $500m$ using a frequency-shift keying (FSK) modulation at $1kbps$. The wake-up signal is sent in the same frequency band as the regular signal. This modem consumes at most $2W$ when transmitting, $44mW$ in reception state and $500\mu W$ in sleep state, including the wake-up circuitry consumption.

3.2 ITACA Modem

The ITACA modem has been designed as an energy-efficient architecture for small/ medium range networks, with low-power UWSN consumption restraints [10]. Its architecture is based on a microcontroler (MCU) that only consumes $24mW$ in reception and $3\mu W$ in sleep state. It is capable of transmitting upto $100m$ using a frequency-shift keying (FSK) modulation at $1kbps$ and consuming $120mW$.

The acoustic wake-up signal is transmitted using an on-off keying (OOK), which is compatible without additional hardware, with the FSK modulation used for the regular transmissions. Hence, this modem also transmits the wake-up signal in the same frequency band as the regular signal.

In order to be able to handle acoustic wake-up signals, the ITACA modem includes an off-the-shelf commercial peripheral, the AS3933 from Austria Microsystems [6]. Since this circuit is intended to be triggered using magnetic coupled signals, a net was specifically designed to adapt the acoustic incoming signals to the RFID based wake-up circuit. This IC with the adaptation net consumes $8.1\mu W$.

Aside from the wake-up tone capability, this modem also includes de possibility, with the same energy consumption, to program and send different wake-up patterns allowing to perform a selective wake-up and only activating the receiving node.

4 The ns-3 Simulator and the Wake-Up Model

The ns-3 is a discrete event simulator for computer and sensor networks. The simulator is organized in modules as shown in Figure 1. The core module offers different libraries to help on the development of models and protocols like smart pointers, trace system, callback objects, etc. [7].

The common module aggregates the data types related to network packets and their headers and the module simulator deals with the simulation time and the different schedulers. Going up though the stack, the node module defines a node in the ns-3 simulator and other different classes. The module mobility is in charge of modelling the mobility of the nodes (in this work the nodes are going to be static).

Following up, the routing, internet-stack and devices modules are the ones that implement the routing protocols like AODV or OSLR; the TCP/IP stack and the devices like Ethernet cards.

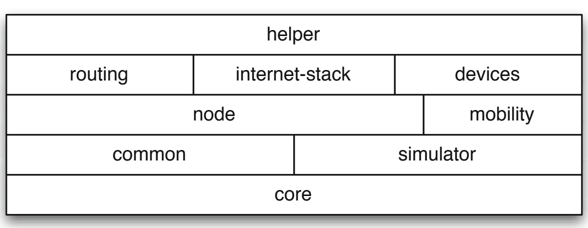


Fig. 1. ns-3 modules

Finally the helper module includes different class definitions implementing an API to facilitate the script programming and the configuration of the simulation to the user.

4.1 Packet Structure

Two different packets are used by the proposed model. The UanPacket, which is included in the standard ns-3 distribution, contains 1 byte for the sender address, 1 byte for the receiver address and 1 byte for the type of the payload. And a newly implemented packet named UanPacketWU, which contains 1 byte for the tone and wake-up pattern.

4.2 Wake-Up Modem Model

In this section the model implementation of this low-power, wake-up system is discussed. As stated before, this model is inspired on the low-cost, low-power, wake-up system by A. Sanchez et al. [11], [10], [12] and the Wills modem [17]. These two modems have similar block diagrams hence, it is easy to compare them in terms of energy consumption by adjusting the consumption power of the different parts.

A simplified component diagram of the ns-3 underwater modem is depicted in Figure 2. The UanNetDevice component models a Network Interface Card (NIC) and is used by the upper layers to send and receive packets to/from the network. The UanMac component models the medium access protocol used by the nodes in the configured network. The ns-3 has some MAC protocols already implemented and ready to use like CW-MAC [9] or the widely known Simple ALOHA.

The UanPhy component models the underwater physical layer and it includes different Signal-to-Noise-Interference Ratio (SNIR) and Packet Error Rate (PER) models. Finally, the UanChannel module models an underwater channel and delivers all the packets to the UanPhy components connected or listening to this specific underwater channel.

The UanPhy component is also connected to a DeviceEnergyModel, which models the energy consumption of the different radio states and, in turn, is connected to an EnergySource, which models different energy containers like batteries.

The presented Wake-Up model is depicted in Figure 3. Like in the regular model, there is one UanNetDevice acting as a NIC card and one UanChannel to emulate the underwater channel. In order to model the regular modem and the wake-up system, two UanPhy and two UanMac are introduced to model the two systems.

The two UanPhy modules are equal in functionality and the only difference between the two is the consumption parameters, which are set to match the consumption parameters of the regular modem and the wake-up system.

The UanMacWU module is responsible for doing the actual channel assessment and sending the wake-up packet (UanPacketWU) before the actual packet that the UanMac module intends to send.

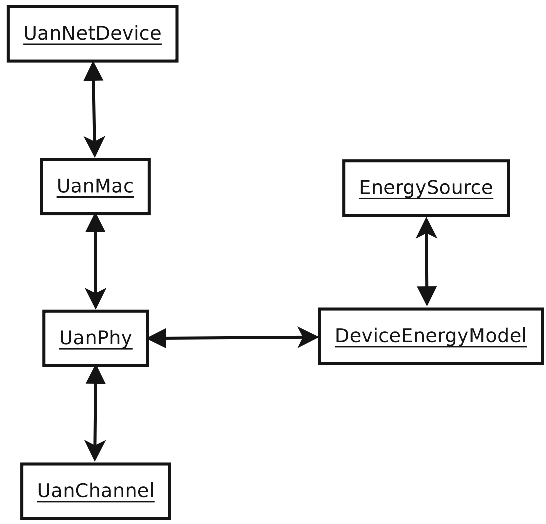


Fig. 2. Simplified component diagram of ns-3 underwater modem

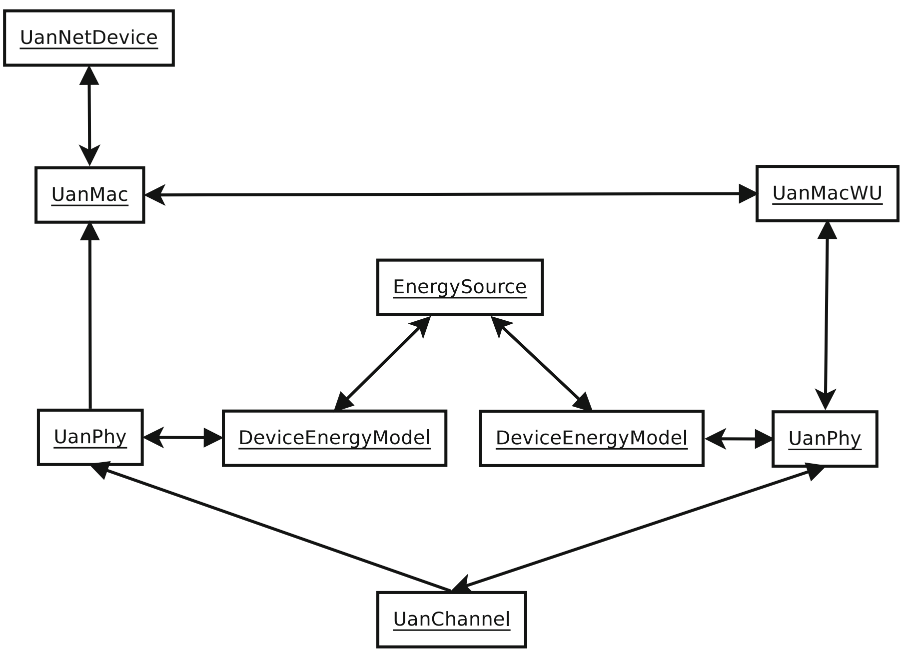


Fig. 3. Simplified component diagram of the proposed underwater wake-up model

The UanMac module is an abstract module. Any class implementing this module should implement the actual medium access algorithm. It has to encapsulate the data that intends to send (namely the actual data from the upper layers or control packets like RTS or CTS) into an UanPacket and has to ask the UanMacWU module if the channel is free. If it is, the UanMac module has to send the packet to the UanMacWU module. If it is not the UanMac module has to decide what to do with this packet, discard it, back-off, etc.

When a packet is received from another node, it will always be preceded by an UanPacketWU hence, the UanMacWU will receive it and see if the packet destination is for this node. If it is not, it will discard the packet. If it is, it will wake-up the UanPhy in charge of the regular radio so it can receive the packet. Figure 4 shows an interaction diagram between the regular radio model and the wake-up model.

In Figure 4(a) the interaction diagram for the sending sequence is depicted. It can be seen how the UanMac module asks the UanMacWU for the current channel status and, if the channel is free, it sends its UanPacket with the data form the upper layers or its own control packets to the UanMacWU. After that, the UanMacWU sends the wake-up packet and the packet from the UanMac immediately after it.

The receiving sequence is shown in Figure 4(b). The UanPhyWU receives from the sending node the wake-up signal. If the signal is for this node, (that is, it is a wake-up tone or a wake-up pattern that matches its own pattern) it wakes-up the UanPhy associated with the UanMac module so it can receive the packet and handle it to the UanMac directly.

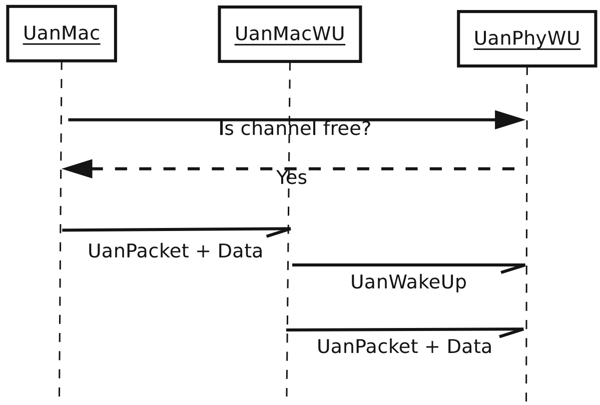
4.3 New MAC Models

A new MAC model, called UanMacWU, was developed for the wake-up model. This MAC is only responsible for sending the wake-up signal before the actual data packet. It is also in charge of receiving the incoming wake-up signal and waking up the modem if the decoded wake-up requires so.

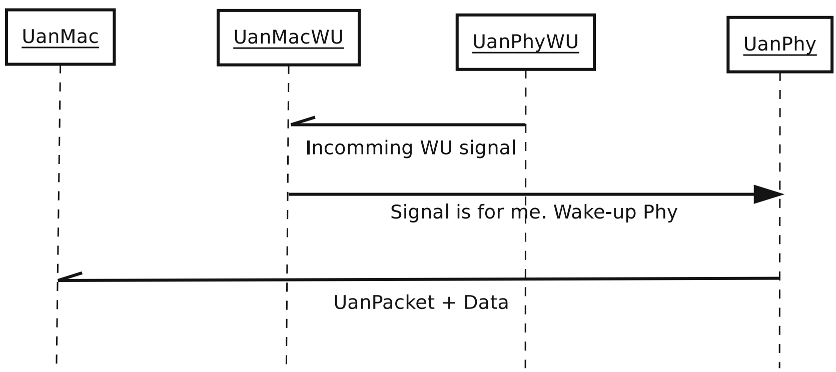
Since the data packet has to be sent after the wake-up packet, it is necessary that the physical layer informs the UanMacWU when a packet has been transmitted. To do so, the UanMacWU also extends the abstract class UanPhyListener provided by the simulator. This way, the UanMacWU can be registered as a listener of its UanPhy and receive when the transmission has finished and start transmitting the actual data packet.

The already developed MAC modules for the ns-3 simulator cannot be directly used with this wake-up model, since they are designed to send their data to a UanPhy module directly and they have to be modified to relay the data to a UanMacWU module.

Another UanMac module was developed in order to test our model. This new MAC module implements an ALOHA-CS (ALOHA with Carrier Sensing) with a FIFO queue for the outgoing packets and a configurable back-off timer.



(a) Sending sequence



(b) Receiving sequence

Fig. 4. Interaction diagram between the radio model and the wake-up model

5 Wake-Up Systems Evaluation

In this section, an evaluation of the two wake-up systems introduced in Section 3 is performed using the proposed wake-up model for the ns-3 simulator.

To that end, the first step has to calculate the transmission state power consumption of the Wills modem. In the original paper [17] the authors only specify the energy consumption when transmitting full-power. Since the ITACA modem is able to transmit upto 100 m, in order to perform a fair comparative, we estimated that the energy consumption of the Wills modem when transmitting to 100 m is 172 mW. Details on how we estimated this value can be found in the appendix.

The other energy consumption parameters used from the Wills modem along with the ones from the ITACA modem can be found in Table 1 and where extracted from [17] for the Wills modem and [10] for the ITACA modem. Although this modems integrate the wake-up systems, this table differentiates between the energy consumption due to the wake-up circuitry and the power consumption due to the regular modem. The reception mode consumption of the Wills wake-up system was set to 0, since this consumption is integrated in the $500\mu W$ of the sleep state of the regular modem [17]. There is no sleep mode for the wake-up, since this system is supposed to always remain awake. Nevertheless, in order to provide the maximum flexibility, the wake-up model allows the researchers to put the wake-up module into a sleep state and specify its energy consumption.

The consumption results of the ITACA modem are consistent with the ones reported in [13] were this modem is fully characterized.

Table 1. Wills and ITACA radios energy consumption

MODE	Wills Wake-up	Wills modem	ITACA wake-up	ITACA modem
TX mode	172 mW	172 mW	120 mW	120 mW
RX mode	0	44 mW	$8.1\mu W$	24 mW
IDLE mode	0	44 mW	$8.1\mu W$	24 mW
SLEEP mode	-	$500\mu W$	-	$3\mu W$

In order to compare the two wake-up systems a set of simulations where performed using the proposed wake-up model with the consumption parameters specified in Table 1. The tests where run using the Aloha-CS medium access protocol and with a simulation time of 1000 s. There were 10 nodes deployed in a square area of 20×20 meters. The transmission speed was set to 1 kbps and the experiments where conducted using the Thorp propagation model. Traffic was generated according to a Poisson process with a generation interval varying between 1 and 100 s. Once the packet was generated source and destination were selected randomly using a uniform distribution. The payload was set to 20 bytes hence, the total length of the data packet was 23 bytes and the length of the wakeup packet 1 byte.

Figure 5 shows the results of the simulations. One can notice how the ITACA modem using the wake-up mode tone outperforms Wills modem by saving 54% more energy with the lowest traffic rate (Wills 1.83 J, ITACA 0.83 J) and a 41% with the highest traffic (Wills 55.08 J, ITACA 32.40 J). But, the highest performance gain comes with the wake-up pattern mode. Using this mode, only the intended receiver of the transmission wakes-up. This provides huge energy savings ranging from 74% upto 80%.

Comparing this pattern mode to the optimum wake-up (where there is no energy consumption from the wake-up circuitry or from transmitting the wake-up signal), Figure 5 shows how the ITACA modem with the pattern mode behaves. Results show how the wake-up energy consumption of the ITACA modem represents only an 8% more in the worst case.

One may want to compare these consumption values with the ones where there is no wake-up system. As a reference, the energy consumption of the ITACA modem when there is 100 seconds of traffic generation interval and there is no wake-up system available would be approximately 24 J, which is much higher than the 0.83 J achieved with the wakeup tone.

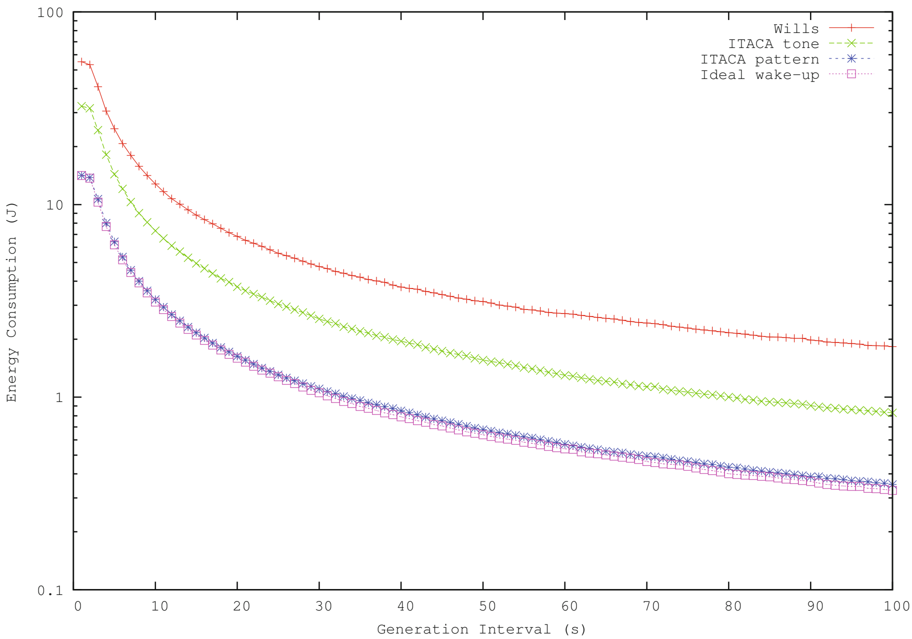


Fig. 5. Comparison results of the two different modems

6 Conclusions

Simulations have proven to greatly facilitate the research and development of new algorithms for underwater sensor networks. By using simulations tools, researchers can develop and test new algorithms before their real deployment, giving insights on the performance an algorithm might have in a real environment. Of course, the system to be simulated has to be as accurately modelled as possible to match the features of the real system.

In this paper, a model of an underwater wake-up modem has been presented. The model has been designed in order to match the most important features of the only two wake-up systems available today, but maintaining certain flexibility to be able to adapt it to new features the researchers might want to test.

Using this model, the two wake-up systems where tested and compared in terms of energy consumption to the optimum wake-up (the one in which the wake-up circuitry consumes nothing) and results showed that the ITACA modem can provide up to 80% energy savings when compared to the Wills modem and only spends 8% more energy than the optimum case.

Future work will include further development of the wake-up model adapting it to allow the transmission of the wake-up signal using different transmission channels and the research and development of new protocols that can take advantage of the wake-up functionality.

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Appendix

Wills modem transmitter is shown in Figure 6. From the data reported in [17], when the output power is set to 2 W the transmission can reach 500 m. Nevertheless, this is the maximum output level and the output power amplifier can be configured using four different gain values. The shorter communication distance, the lower power is needed to maintain the same communication performance. Therefore, to make a faithful comparison between the ITACA modem and Wills modem, the output power needs to be reduced to match 100 m.

To calculate the amount of power in transmission that the Wills modem needs to reach 100 m communications, the following statements are assumed:

1. Wills modem supports four discrete transmission power levels: 15dBm, 21dBm, 27dBm and 33dBm [17].
2. Output power should be near to 108 mW (20.3 dBm), which is the power reported in [12] to reach 100 m using ITACA modem.
3. TX power consumption is mainly due to two main blocks: power amplifier and node micro-controller. The rest of the modem elements are considered to be switched off or their power consumption is considered negligible.

$$P_{supply}(mW) = \frac{P_{out}(mW)}{\eta_{amplifier}} \tag{1}$$

The minimum value found to reach 100 m. was reported in [12] to be 20.3 dBm. Hence, we have to choose the higher value closer to this one in the Wills power amplifier, which is 21 dBm.

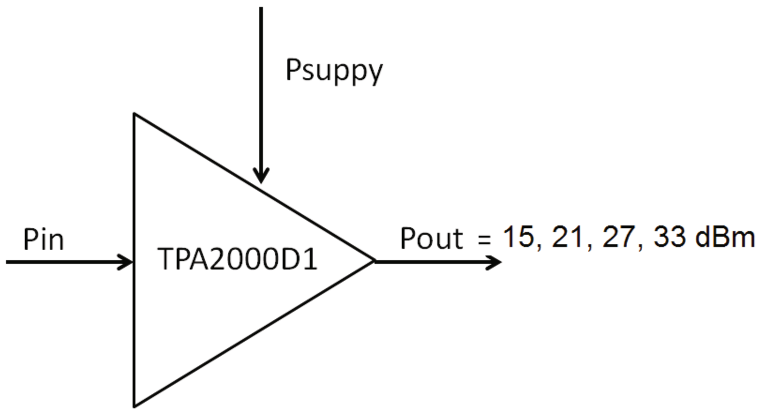

Fig. 6. Wills Modem acoustic wave transmitter diagram

The energy demanded to the power supply from the amplifier output power is obtained using expression (1). Wills output amplifier efficiency (η) is around 0.85 [16]. So, we estimate that Wills power consumption to transmit messages to nodes placed 100 m far is 148 mW (21.7 dBm). This value only accounts to the power amplifier, Wills modem architecture embeds a Mica, which power consumption in active mode corresponds to 24 mW [5]. Concluding, we estimate that Wills power consumption for 100 meter links in TX mode is 172 mW (22.3 dBm).