Advanced Acoustic Wake-up System for Underwater Sensor Networks

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Abstract—**This paper presents a low-cost and low-power consumption asynchronous Wake-Up (WU) development to Underwater Wireless Sensor Networks (UWSN).**

An asynchronous WU offers important advantages for energy-aware network polices, however it needs some specific hardware, an optimal configuration of system facilities and the interconnection with a core control unit.

This proposed WU implementation has been specifically designed to be used in acoustic underwater modems, able to react to external acoustic stimuli. Both the modem and the Wake-Up system use a unique piezoelectric transducer dissipating, to our knowledge, the lowest power published until now. Moreover, the system is able to detect both simple tones and predefined bit patterns, being able to wake up a network node UWSN individually or even to different nodes at the same time.

Keywords— Underwater Networks; Wireless Sensor Networks; Acoustic Modems; Wake up; Low Power

I. INTRODUCTION

Underwater Wireless Sensor Network (UWSN) development is of current interest due to their potential number of attractive applications.

An UWSN is physically composed by a number of nodes, the smallest computational unit in a network. Nodes are self-powered by batteries or they can include some energy-harvesting resource. In both cases, the tendency is the reduction of both the size and cost of nodes and consequently, the size of its batteries. Thus, the design must be oriented to consume as low power as possible in order to extend nodes operational life.

In this line, modern microcontrollers usually offer several operating modes which, depending on performance necessities, can switch between different clock sources in order to minimize its power consumption. Among operating modes, the 'sleep mode' reduces power consumption to its minimum by turning off the Central Processing Unit (CPU) and attached peripherals as much as possible. Exploiting this sleep mode is a very interesting option in networks with low traffic demand and, consequently, low communication activity. However, as long as messages cannot be sent nor received by the wireless interface in sleep mode, the microcontroller needs a way to wake up and reactivate its normal activity.

This paper presents a detailed description of an asynchronous Wake-Up system specifically designed to underwater communication with acoustic link. The design observed under two scenarios, numerical computing simulation and real on sea waters. Firstly, the paper presents the MATLAB-Simulink model whose results have been explored to evaluate final system reliability.

The paper is organized as follows. Section II sets the paper framework. Section II summarizes the most relevant hardware features of an acoustic modem previously developed to the present work. Section IV presents the low-power proposed WU circuit. Section V describes how the WU resource is extended in order to detect multiple patterns. Section VI describes the Simulink model of the WU system. Section VII presents and evaluates some practical experiences carried out to evaluate the system performance. Section VIII verifies the system. And finally, section VIII concludes the paper.

II. RELATED WORK

Strategies to Wake-Up (WU) a node can be grouped into synchronous or asynchronous. Synchronous WU strategies are based on time sharing and synchronization, while asynchronous WU strategies depend on external stimuli.

Synchronous WU strategies need very simple additional hardware. Time synchronization can be kept by using a Real Time Clock (RTC) or even a timer. This hardware is well known, usually dissipates very low power [1] and even is integrated as on-chip peripheral in several state-of-the-art microcontrollers [2]. Nevertheless, synchronous WU strategies are based on the premise that two nodes that want to communicate will switch on their wireless interfaces at the same time just synchronizing their corresponding internal clocks. Time-driven protocols trust energy saving to the efficiency of their clock synchronization mechanisms. Generally speaking, synchronous WU strategies present an additional energy waste to the minimum required to transmit or receive [3]. Moreover, in an event-driven communication, which starts when some specific event is recognized, the wireless interface tends to remain active more time than needed to complete a packet transmission.

Asynchronous WU strategies, however, need much more specific hardware. A node must be able to react to certain stimuli. For example, an acoustic signal can be used to reactivate the node, but it will need an Acoustic Triggered Wake-Up (AT-WU) circuit. This circuit must dissipate as low power as possible since it remains always active either in microcontroller sleep mode or in active modes. However, the extra energetic effort done by the node is worthily reinvested because it has been proved that asynchronous WU can reduce overall network power consumption more than synchronous WU [4]. Asynchronous WU is close to the optimal case of opening the wireless interface only to transmit or receive a packet in both time-driven and event-driven protocols.

Recently, Harris, Stojanovic and Zorzi published a work comparing both WU techniques simulating the energy consumption levels of a synchronous WU solution as STEM [3] and a wake up asynchronous design [5] (called in the paper the wake up mode) [4]. Authors concluded that "*for underwater sensor networks where the expected traffic generation is less than one packet per node per few hours, the wakeup mode will save energy over sleep cycling both in terms of the greatest energy consumption of a single node, thereby increasing the network lifetime by delaying the first node death*".

However, very little work has been done about asynchronous AT-WU. The main reference so far is Wills, Ye and Heidemann work in 2006 [5]. This work includes two important characteristics expected in any asynchronous WU system: inexpensive and low-power consumption. The complete WU circuit draws 500µW when waiting for an incoming valid wake up signal.

However, there exist terrestrial WU circuits that dissipate less than 100µW waiting. State-of-the-art asynchronous WU systems for WSN dissipate 52µW [6], 11µW [7] and 12.6µW [8] as shown in TABLE I. These works agree to use On-Off-Keying (OOK) in the wake-up operation in order to save energy.

So this paper proposes the adaptation of terrestrial WU techniques to the underwater scenario, obtaining a reliable but ultra-low power Acoustic Triggered Wake-Up circuit.

A previous work in terrestrial networks [9] showed that no extra hardware is needed to generate and transmit a WU signal. But, on the other side, additional hardware is needed on the receiver to analyse incoming signals and to wake up the microcontroller. As a result, the modem abstraction block diagram is shown in Fig. 1 in which a specific peripheral has been added only to the receiver while its own acoustic modem wireless interface is reused to generate and transmit the OOK WU signal. This peripheral, a low-cost commercial available off-the-shelf IC, is usually found to terrestrial RFID (Radio Frequency IDentification).

TABLE I.
STATE-OF-THE-ART OF RT-WU SYSTEMS

SOLUTION	FREQ (MHz)	SUPPLY (V)	PWR. (µW)	SENS. (dBm)
ITACA [9]	868.3	3.0	8.7	-53
Berkeley 2008 [6]	2000	0.5	52	-72
Durante [7]	2400	1.5	11	-57
J. Ansari [8]	869	3.0	12.6	n/a

The overall modem, including the WU peripheral, dissipates 10µW waiting, which absolutely agrees with power limit constrains of current underwater wireless communication devices. In fact, ITACA WU power consumption is the lowest of the state-of-the-art RT-WU systems that appear in TABLE I. Thus, the proposed WU circuit is a very interesting resource in the design of low-power consumption UWSN, helping to extend network lifetime for a reasonable price. Finally, our results can be exported to other networks simulation tools as ns-3 [10] to evaluate final system reliability.

III. PREVIOUS HARDWARE

The AT-WU circuit is modular and therefore it is not restricted to a specific acoustic modem. However, the overall modem consumption obviously depends on the whole architecture.

The ITACA institute has developed an innovative modem mainly focusing on two parameters: cost and power consumption. Its nominal data rate is 1kbps. The implementation is suitable to short range distance dissipating 16mW to 68mW in transmission mode. However, 100 meters in shallow water have been successfully reached consuming 120mW (reported in [11]). As can be seen in TABLE II, power consumption is the lowest of the state-of-the-art of research acoustic modems but still presents a compromise solution with data rate.

TABLE II.
STATE-OF-THE-ART OF ACOUSTIC MODEMS USED IN UNDERWATER SENSOR NETWORKS

Modem	ITACA [11]	Freitag [12]	Iltis [13]	Wills [5]	Parsons [14]
Modulation	FSK	FHFSK-PSK	M-FSK	FSK	FSK
Data rate (bps)	1000	5000	133	600	31
Sleep Power (µW)	3	-	>100	>500	13.6
RX Power (mW)	24	> 500	>300	> 25	65
TX Power (mW)	120 *	> 500	>300	> 25	243
Distance (m)	100	2-4 k	-	500	100
Sensitivity (µV)	30	-	-	10	-

* TX power corresponds to 108 mW power amplifier stage (100m distance) and 12 mW MCU.

The modem has been equipped with a commercial HUMMIMBIRD XP 9 10 piezoelectric transducer. Although this transducer was originally commercialized for other applications such as fish-finding or depth-metering, it has been successfully re-targeted for acoustic communications. The architecture is based on a microcontroller. The modem implements a mixed Analog-Digital Central Processing Unit (CPU) capable of synchronous FSK modulating and demodulating. The possible operating modes within this architecture are the following:

A. Sleep mode:

Modem is turned off and messages cannot be neither sent nor received. Node microcontroller can be activated by an event or a port change (e.g. external push). Power consumption is only 3µW (@3.0VDC), which is the lowest ever reported for such application as compared in TABLE II.

B. Receiving (RX):

ITACA modem only implements one receiving mode in which frames are decoded and error-free packet reception are announced to protocol upper layers. Power consumption is 24mW (@3.0VDC). Approximately half of this power consumption is used to amplify and filter the received signal, while the computing unit consumes the rest to run a demodulation algorithm. Receiver amplifier is based on a passive T-structure LC pass-band filter cascaded to a Variable Gain Amplifier (VGA) with Automatic Gain Control (AGC) from 0dB do 80 dB. Measured sensitivity is around 30µV.

C. Transmitting (TX):

Power amplifier stages consumption depends on the transmission distance to be covered. To reduce wasted power, ITACA modem implements an innovative Digitally-controlled Push-Pull B-class (D-PP-B) amplifier with 75% measured efficiency.

In an ideal scenario, the microcontroller should remain in sleep mode as much time as possible, consuming less than 3μW when no transmission, reception or sensor measure is required.

IV. WAKE-UP SYSTEM DESIGN

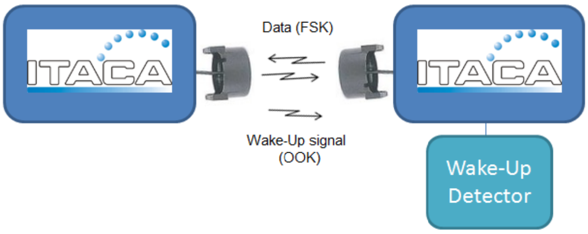

Fig. 1 Wake-Up Overall System

Joining up the WU peripheral to the ITACA modem does not imply any change in the architecture of the modem. As shown in Fig. 1 a WU system involves additional hardware on the receiver to recognize a valid WU signal and to wake up the main Micro-Controller Unit (MCU), while WU signal transmission does not need additional hardware. Fig. 2 depicts the block diagram of ITACA modem modified to embed the WU circuit.

When the MCU is in sleep mode, the WU circuit waits listening to the channel. If it detects a possible incoming WU signal, this circuit must process it, waking up the MCU just in case of a positive recognition. Moreover, this circuit is also active when the MCU is active, an interesting feature to recognize multiple WU requests.

The WU signal is On-Off Keyed, attending to the simplicity of OOK demodulation circuits. For example, the simplest OOK demodulator is known as envelope detector and it is formed by a diode and a capacitor; this system dissipates no power. However, a FSK demodulator based on Phase-Locked-Loop (PLL), as used in ITACA modem [1], dissipates 12mW. Thus, the consumption of a WU circuit based on OOK demodulation will be lower than the one using Frequency-Shift-Keying.

Besides, the WU circuit is expected to perform extra signal processing to avoid false Wake-Up detections, little more complex than simple demodulation.

To implement the described features, the presented WU system has been designed using the AS3933 of Austria Microsystems [15]. It is a commercial WU Integrated Circuit low-cost receiver, ideal for RFID tags, since it was not originally designed for acoustic signal transmission. The novelty of this work is the adaptation of this IC into a WU acoustic underwater receiver.

A. *Wake-Up Signal*

1) *WU Signal Medium Transmission*

Through water channel, a node transmits both wake-up signal and data. The wake-up signal will be transmitted and received by every node within transmission range. This wake-up signal is more complex than a single tone. It contains identification information which is used by each AT-WU circuit to compare it with its assigned recognition pattern. Only in case of matching, the AT-WU circuit will generate the interrupt signal that wakes-up the microcontroller.

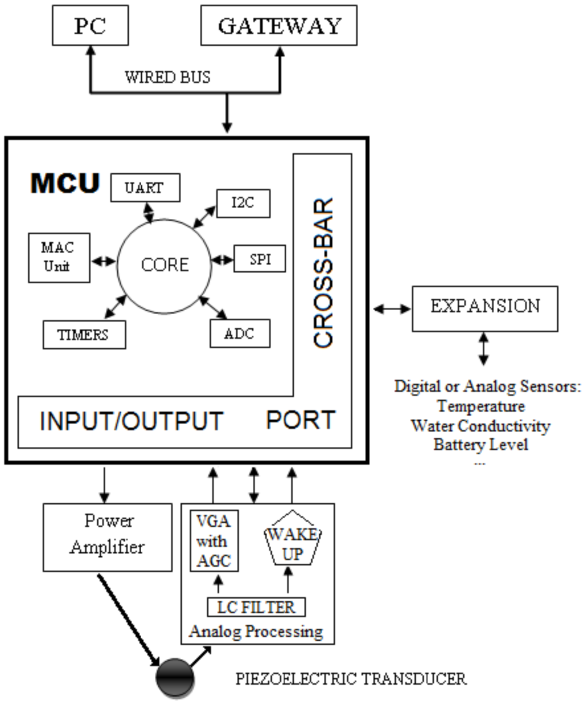

Fig. 2 ITACA Modem with Asynchronous WU System

2) *WU Signal Frequency Band*

In the presented prototype implementation, frequency band to both signal wake-up and data is the same (85 kHz) in order to use the same transducer. It simplifies the architecture, but it does not relieve the network of data-WU signals collisions. However, this coincidence is not mandatory, as it will be discussed later, attending to AT-WU design portability.

3) *WU Signal Modulation*

Wake-up signal is OOK (On-Off-Keying) modulated-depicted in Fig. 3.

An OOK pattern example is shown in Fig. 4. It consists of three different parts: carrier, preamble and Manchester coded pattern.

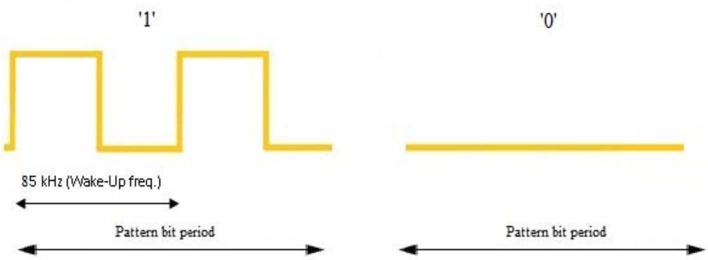

Fig. 3 OOK Modulation Example

When correlator detects a matching condition, it will set a flag to the MCU. In case of tone detection, only carrier signal is needed to set this flag.

B. *Wake-Up Transmitter*

When a node, setting up as transmitter, needs to establish communication with another node in the network, it will start this communication emitting a WU signal.

The WU signal can be configured with two different complexity levels: from a single carrier frequency tone, to a bit chain with a specific pattern. This pattern could be different to every node on the network, allowing selective wake-ups.

As observed in Fig. 1 and Fig. 2, the transmission of a WU signal neither requires additional hardware nor modifications on the existing modem due to OOK modulation can be easily implemented in any microcontroller based architecture. Even though data transmission is FS-Keyed, OOK is compatible by simply switching node power amplifier output on and off according to the transmitted symbol. Bit synchronism is achieved by Manchester coding.

C. Wake-Up Receiver

On the receiver side, specific hardware is required. This hardware will be always active, listening to the channel, waiting for wake-up signals. Thus, it should dissipate as low power as possible.

Best solutions on terrestrial RT-WU systems are based on superheterodyne structures [9]. Incoming signal is shifted to a lower Intermediate Frequency (IF). The use of such structure reports higher wake-up detection ranges with lower power consumption.

For example, in [9], authors present a RT-WU solution based on an existing commercial IC originally commercialized to RFID applications. Austria Microsystems AS3930 detects 125 kHz (110-140 kHz) tones. Moreover, the AS3930 chip is able to detect 8- and 16- bit patterns. Additionally to the AS3930 IC, the RT-WU solution in [9] combines the RFID 125 kHz with an ISM band (868 MHz to data transmission).

Austria Microsystems has made an interesting effort to release AS3933 [15]. Different blocks, essential to wake-up effective detection, are now embedded. For example, software reconfigurable input impedance matching net, Automatic Gain Control (AGC), envelope detector or signal correlator. However, this IC was originally designed to be triggered using magnetic coupled signals with a coil antenna for RFID systems. Therefore, a net must be specially designed that matches both impedances and suitably couples the acoustic incoming signal to the RFID based WU circuit. Thus, the WU circuit incorporates a specific matching net formed by a 3-stage T-structure band-pass filter with passive inductors and capacitors.

During the implementation, it was found that this T-structure with inductors and capacitors is the most suitable structure since capacitors avoid any circuit bias modification and inductors mimic coil-antenna magnetic coupling.

The final WU receiver (WU-RX) presents the following features:

- Wide frequency range. 15-150 kHz tones with pattern recognition. One over five different bands can be selected: 15-23, 23-40, 40-65, 65-95 and 95-150 kHz.
- Tone, 16 and 32 bit pattern recognition.
- Operating supply voltage from 2.4V to 3.6V.
- 2.7 µA (@3.0VDC) consumption in listening mode.
- False wake-up control via wake-up reporting and counter.
- ASK receiver with Manchester coding capability.
- Additional low-power sleep timer with wake-up capability.
- Reconfigurable via SPI (Serial Peripheral Interface).

D. Wake-Up Hardware Integration

The RX analog processing stage of the original modem presented in [1] has been improved – Fig. 1. This block has been designed to both filter and amplify incoming FSK signal and to detect incoming valid WU signals.

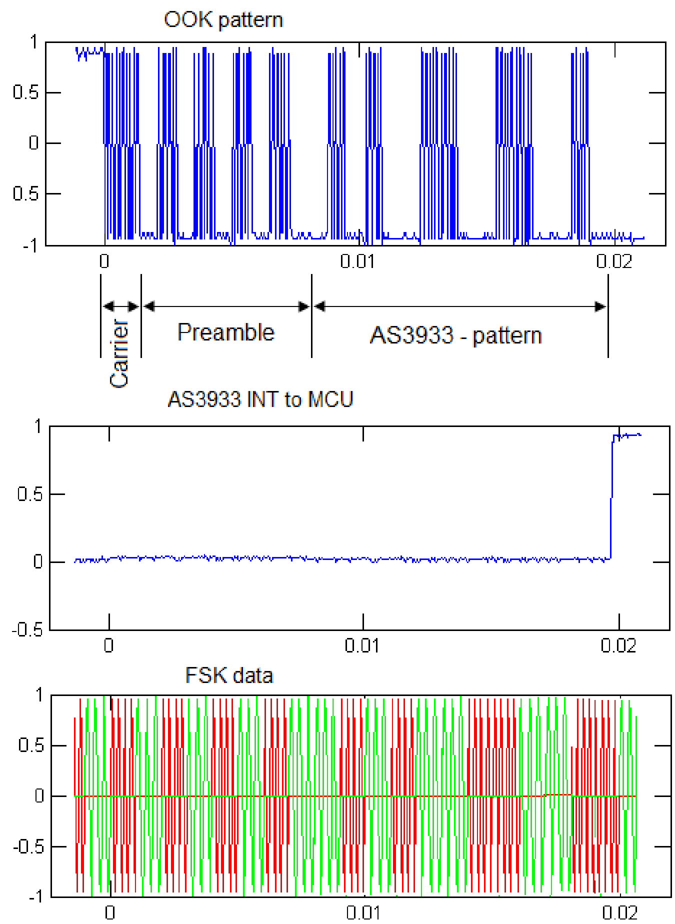

Fig. 4 AS3933 Pattern Detection Example Compared to the Same Pattern FS-Keyed.

On the one hand, to FSK demodulation, the needed analog processing circuit is described in Fig. 5. It includes a signal Variable Gain Amplifier (VGA) with Automatic Gain Control and a pass-band filter. Its output is connected to the FSK demodulator.

On the other hand, once a WU signal is received, decoded and verified as valid, the WU peripheral sets a flag to the MCU. The WU signal recognition is expected to cause a MCU operating radio mode change managed by a suitable software interruption handler, increasing flexibility.

FSK signals cannot generate valid OOK patterns – Fig. 4 - and vice-versa. Moreover, in case the modem is in sleep mode, FSK demodulation is not performed - MCU does not execute any instruction and the receiving pre-amplifier is disconnected – and the incoming signal is only processed by the AS3933 IC.

However, when the modem is active, the implementation contemplates two possibilities:

- If the incoming signal is On-Off-Keyed modulated, the AS3933 will work on the signal verification while no effective information will be obtained by the FSK demodulator.
- If the incoming signal is FSK modulated, the AS3933 will not recognize any valid WU signal.

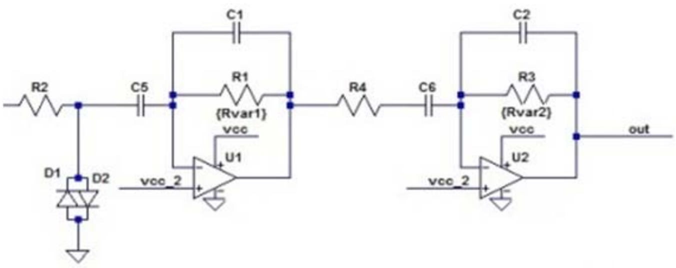

Fig. 5 Receiving Pre-amplifier Schematic

V. MULTIPLE WU PATTERN RECOGNITION

Although it would be very interesting to selectively Wake-Up one node of the network with more than one pattern (for example, to different radio mode changes) the AS3933 chip is only able to detect one single OOK Manchester coded pattern.

The following example shows the real advantage of multiple pattern detection: broadcast diffusions in unicast networks. On the one hand, if each node were only capable of waking up by the detection of a unique pattern – a node pattern non-coincident to any other network node - , broadcast would only be accomplished by emitting the whole set of network patterns, one per node. On the other hand, if all nodes were woken up with the same pattern – a network pattern coincident in every network node - all the nodes would be awaken with every link request even when it would be a unicast transmission. In both cases, energy wasted is not negligible.

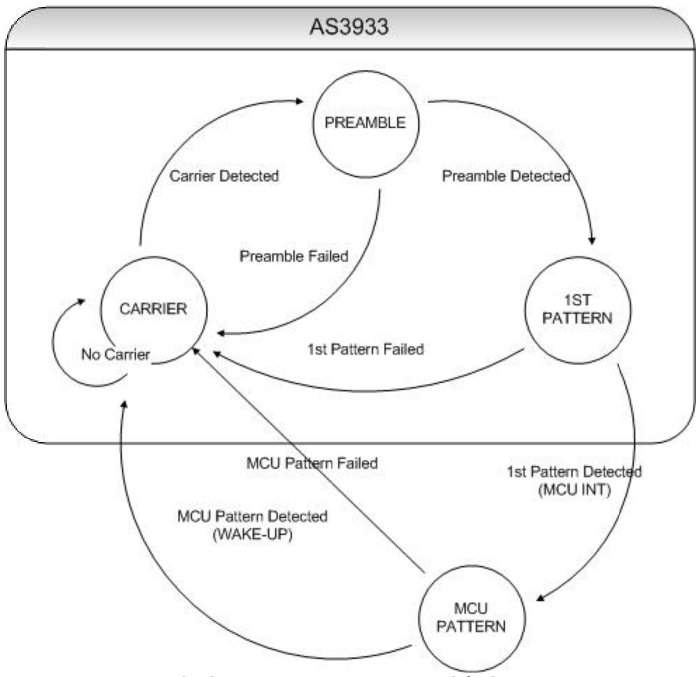

Fig. 6 Multiple Pattern Recognition Simplified State Diagram

Other interesting application is control packet reduction. Control packets can be avoided by activating the node in different modes attending to the WU pattern received. For example, a router in a multi-hop network can be asked for receiving an incoming packet or for sending a pending packet depending on the WU signal received. Further control packets can be avoided and some energy is consequently saved.

To multiple patterns recognition, WU signal has been extended, as can be seen in Fig. 7: carrier; preamble; 8 or 16 bits pattern to be detected by AS3933 IC; and m additional bits pattern to be detected by the MCU. Both patterns are OOK modulated while Manchester decoding is required to synchronize bit reception.

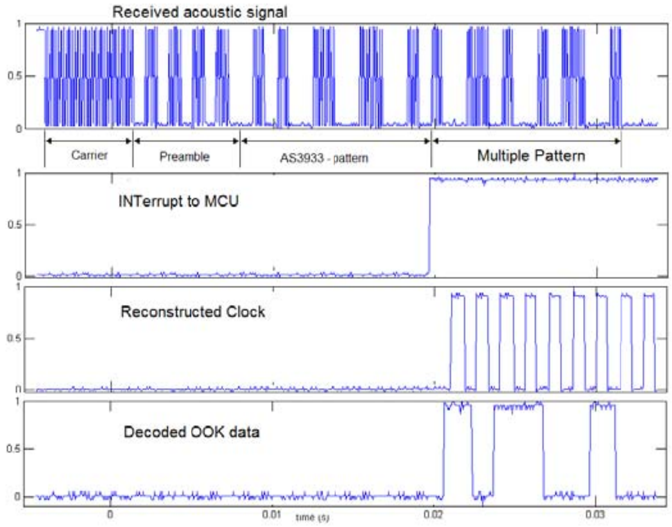

Fig. 7 Multiple Wake-Up Pattern Detection Signals

The proposed multiple pattern detection algorithm is shown in Fig. 6:

- The receiver remains in sleep mode while the WU peripheral listens to the channel – Carrier state. Dissipation is only 8.1µW.
- After detecting a carrier signal, the WU peripheral validates preamble and AS3933-pattern. When a valid sequence is detected, the peripheral sets a flag– MCU INT – to wake up the MCU.
- In MCU PATTERN state, the MCU reads m additional bits. In order to save energy, system clock frequency has been configured to 406 kHz (60 times slower than system clock in FSK TX and RX), which implies a power consumption of 540µW in reception only during 16 ms or 32 ms for m = 8 or m = 16. This power consumption overhead is evaluated in later sections.

VI. AT-WU SYSTEM SIMULINK MODEL

In recent years, several Works on underwater acoustic channel have been published [17]. Real data concerning depth and sea floor materials can be imported from different global databases to these models. As resulting, communication conditions in certain localization can be modelled beforehand estimating final system behaviour.

So it would be desirable to accurately and quickly evaluate network performance with AT-WU capability in a predefined scenario. A model integrated in a simulation tool is essential to reach this goal. Attending to its simplicity and its potential for future extensions, we have decided to develop this model by using Simulink environment of Matlab [18].

In Fig. 8 ITACA RX WU model is shown. The main modules embedded in this subsystem have been modelled and included inside this model.

Amplitude is normalized using a Variable Gain Amplifier with Automatic Gain Control. OOK decoded signal is correlated with a programmable correlator. Both tone and Manchester coded patterns have been considered by the correlator. The results are the correlation of the incoming signal with the programmed pattern (percentage) and WU valid signal detection (MCU INT). MCU INT is set by comparing the current correlation value with a certain threshold, depending on the programmable tolerance configuration.

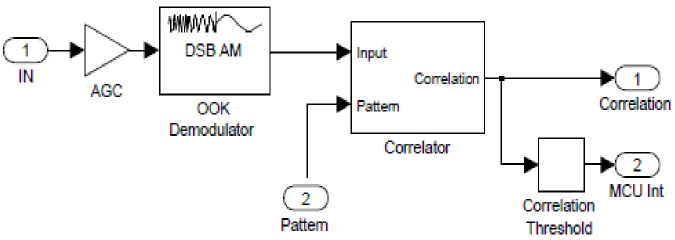

Fig. 8 ITACA WU-RX Block Diagram Model

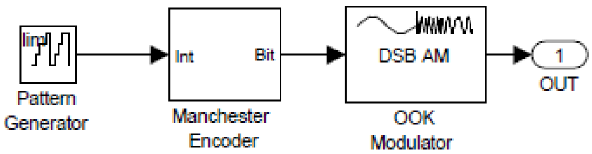

Fig. 9 AT-WU Manchester OOK Generator

Although AT-WU is the only hardware subsystem to be added to an existing modem, OOK modulation and Manchester coding software functions should be also modelled. Simulink suite allows making an abstraction of both hardware and software to implement the simplest functional diagram blocks. The result of the WU signal transmission is shown in Fig. 9. In this case any 8-bits patterns from 0x00 to 0xff are sequentially generated, encoded and transmitted. However, the proposed pattern generator admits other possibilities such as random or constant generation.

Finally, both AT-WU transmitted signal and AT-WU reception circuit are interconnected by using an underwater acoustic channel model. The overall WU system is modelled in Fig. 10 in which Pattern TX corresponds to Fig. 9 and RX WU corresponds to Fig. 8.

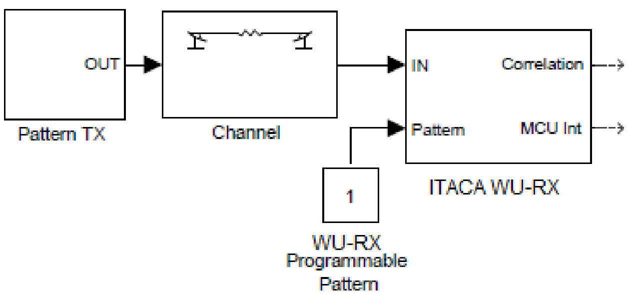

Fig. 10 AT-WU Whole System

VII. WAKE-UP SYSTEM EVALUATION

To carry out a full evaluation, the proposed solution has been prototyped and adapted to the modem hardware described in Section III. Now, we proceed to describe several evaluation tests.

A. OOK Pattern Robustness

The wake-up circuit topology itself can lead to some pattern aliasing: more than one bit string can cause positive pattern detection. The inner flexibility of the correlator causes this aliasing effect, more accentuated to those patterns whose Manchester encoding presents similitude with the preamble structure.

For example, it has been experimentally realized that 0xff pattern is easily confused with 0x00 pattern by the internal correlator.

1) Correlation Tests

To estimate error probability and pattern detection uncertainty, we have cross-correlated all possible programmable patterns. Carrier and preamble have been also considered in this experiment to obtain a realistic estimation.

Fig. 11 is built on 8-bits cross-correlated patterns. Only those with more than 87.5% correlation (100% corresponds to perfect match) are marked in the figure. Each pattern has a 100% correlation with itself (diagonal line in Fig. 11). However, undesirable 100% correlations also exist.

For example, Fig. 12 details the cross-correlation of 0x00 pattern. This figure shows a 100% correlation with both itself and 0xff also. Thus, the configuration and emission of 0x00 pattern will cause a true valid detection but also it occurs a false wake-up with the emission of 0xff pattern.

In fact, we have observed that patterns with a cross-correlation over 87.5% also cause false wake-up detections due to correlator tolerance. We called this effect as aliasing into the next experimental test.

It has been also simulated the RX WU model with all the possible incoming 8-bits strings, when 0x00 is actually the configured pattern. Simulation trace is shown in Fig. 13. If simulation results are compared with the values measured in the reliability test for the same pattern (Fig. 12), we observe that the curves perfectly fit.

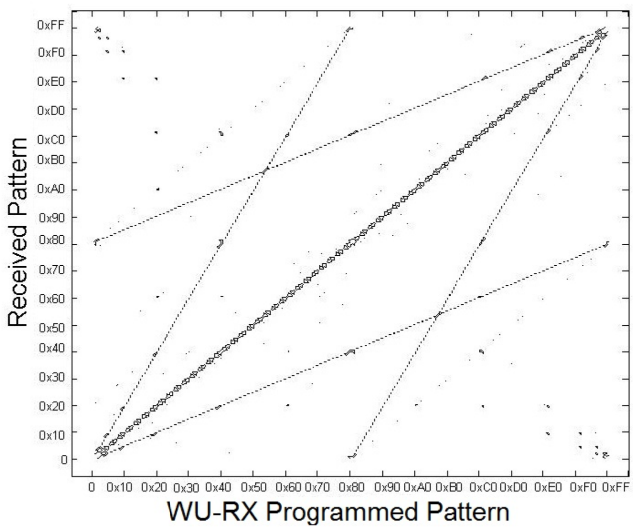

Fig. 11 Cross Correlated Pre-programmed in the WU-RX Module (AS3933) and Received Patterns

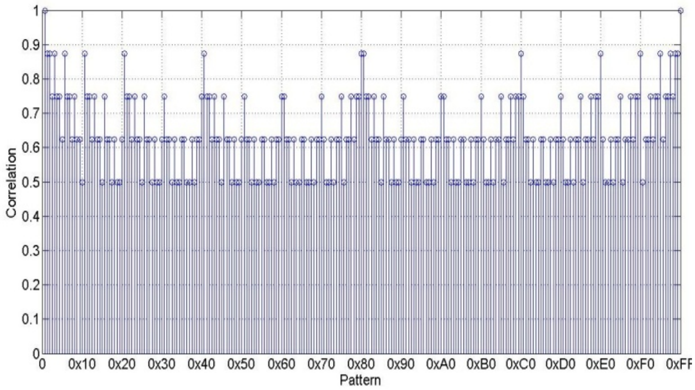

Fig. 12 0x00 Pattern Cross-correlation

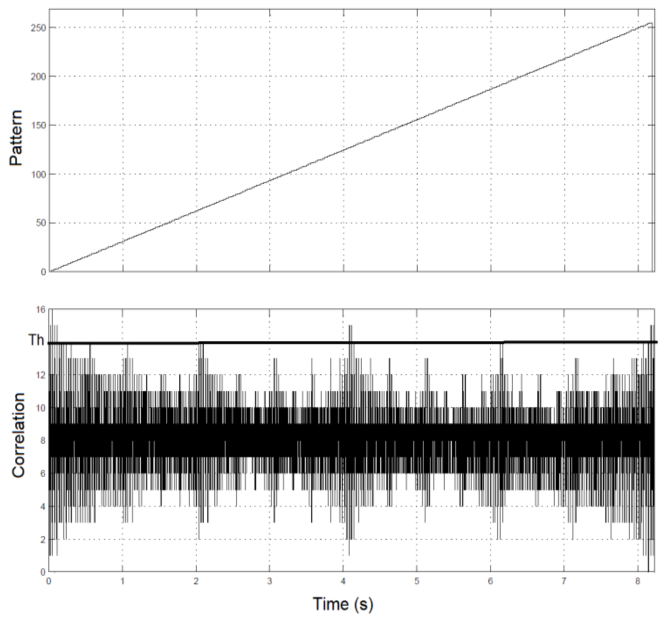

Fig. 13 Simulink Simulation Results Generating All the Possible Patterns. AS3933 Pattern: 0x00.

2) False Wake-ups and Non-detections

Two modems were submerged during 24 hours in a water tank. One of these modems was constantly sending WU signals with 16 different 8-bit array patterns – including 0x00 and 0xff. The receiver modem should only recognize one of these 16 patterns.

Two parameters have been observed with this experiment. Firstly, it was measured the number of false wake-ups which lead the modem to become unexpectedly active. Secondly, the number of detection failures when the emitted pattern is coincident with the configured one but pattern recognition fails was also measured. Two scenarios were set. In the first one, the WU pattern configured into the receiver was never sent. This scenario characterizes false waking up probability. In the second scenario, the configured WU pattern is emitted periodically. Results are shown in 0.

The non-emitted column corresponds with the first scenario. Neither false wake-ups nor non-detected pattern were reported.

However, in case of patterns with high aliasing probability (such as the 0x00 example) the false wake-ups probability is higher of 60%.

As another fourteen different patterns were also transmitted with lower cross-correlation than 87%, false wake-up detection probability disappears.

If patterns with aliasing are avoided, the performance of the WU system increases. In the worst observed case, no false wake-ups were reported while non-detections occur at a rate of 0.6% (Fig. 14 non-aliasing column).

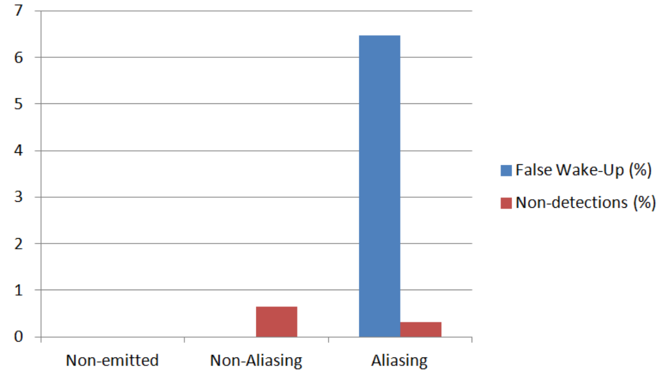

Fig. 14 Error Rate Experiments Results in Worst Case

B. Energy Evaluation

A wake-up solution which consumes 8.7 μW means a reduction on 98.3% compared with [5]. It is a huge improvement but also was needed. ITACA modem power consumption is far below of previous acoustic modems for UWSN. Thus, the impact of the AT-WU on the modem must be dimensioned to this consumption. The objective of this section is to compare the overhead of two acoustic wake-up solutions: Wills [5] and the proposed one in an ideal controlled scenario with only two nodes.

The comparison will use the following *ITACA modem parameters*: Power consumption to communicate 25 vertical meters is RX 24mW and TX 28mW. Sleep mode consumption is 3μW. Messages are assumed to be of 64 bytes, which at 1kbps data rate is translated in 0.512s to either transmit or receive a packet.

Wills AT-WU module has been already joined up to WHOI modem [12] and tested in a previous study on wake-up impact on UWSN [4]. However, to the present estimations, both modules Wills and the proposed AT-WU will be connected to the ITACA modem.

Besides, two additional estimations will be added to the comparison which will act as energy consumption boundaries: *idle* and *optimal*. On the one hand, *idle* boundary assumes that a node is always listening to the channel (RX) waiting for new messages. This scenario can be considered a worst case scenario since the node does not exploit low power modes. On the other hand, *optimal* boundary assumes that a node is only listening while a packet is received, going to sleep the rest of the time. Since it assumes perfect synchronization, it is the lowest possible power consumption scenario. These boundaries have been also proposed in a previous study on wake-up impact on UWSN [4]. Other alternatives based on varying listening duty cycles, e.g. STEM [3], have not been considered since they are enclosed between *idle* and *optimal* boundaries.

It will be evaluated power consumption of a single node in a simple scenario with the following duty cycle sequence: the node receives a message, once received, it sends back an Acknowledgement (ACK) packet and waits for next incoming packet in three possible modes, depending on the case studied: sleep mode (in *optimal*), RX (in *idle*) or sleeping with the attached AT-WU active (in *Wills or ITACA-WU*). This cycle longs around 1 second TX+RX plus 60 seconds into sleep repeated cyclically.

1) Packet Generation Rate Analysis

Experimental results are shown in Fig. 15. Inter-arrival time between packets ranges from 0s to 300s:

- When packets are continuously received (the shortest interval between packets), all solutions achieve the same power performance.
- Up to one minute time interval between packets (maximum period considered in work [4]) both Wills and ITACA AT-WU solutions improve *idle* boundary around 75%.
- With five minutes time interval, which is not far from a real underwater case scenario, significant differences come up. This difference comes from both the AT-WU module consumption reduction together with the low modem consumption in sleep time.

Both configurations single and multiple pattern capability are analysed in Fig. 11 (single and MCU-Pattern). We assumed in previous sections that multiple capability still agreed with original system constraints although MCU is actually activated but for a very short time (16 to 32 ms) consuming 540μW. As can be seen in is Fig. 15, energy wasted by multiple pattern recognition is practically negligible compared to single pattern.

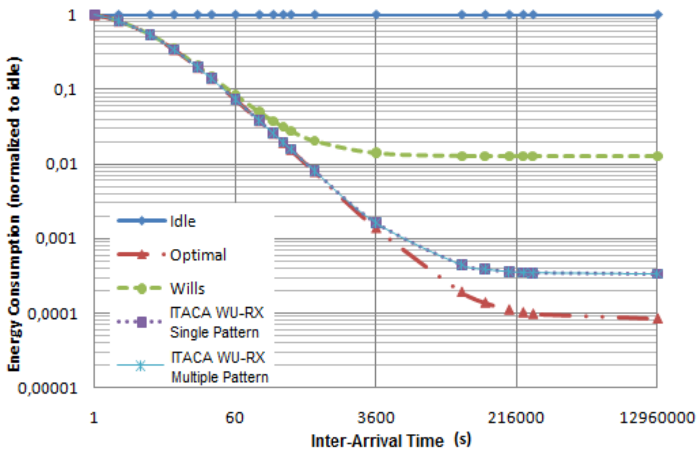

Fig. 15 Energy Consumed by Different Configurations Compared to IDLE with Different Generation Intervals

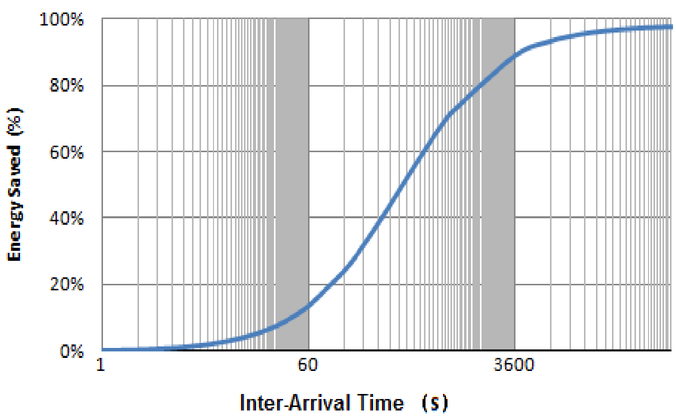

Fig. 16 Energy Saved If AS3933 Is Used Instead of Wills Wake-up [12]

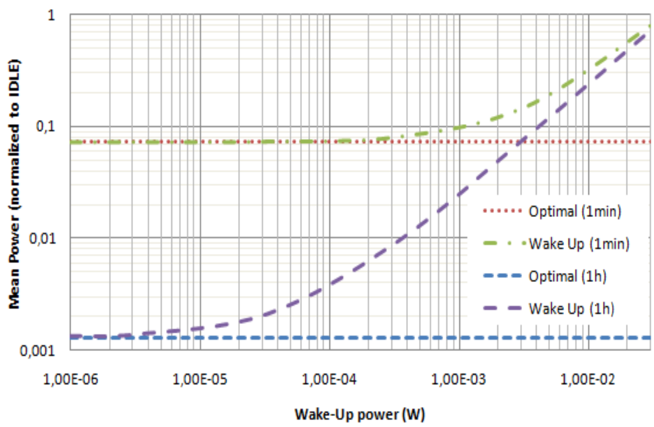

Fig. 17 Overall Power Consumption Attending to Wake-up System Power. Y-axys: mean power consumed normalized to *idle.* X-axis: Wake-Up circuit consumption.

Fig. 16 shows energy saving within two possible realistic time interval boundaries. On the one hand, with packets received every minute, our solution saves 13% compared to Wills solution.

On the other hand, with ultra low traffic demand, e.g. 1 packet per hour, 88% energy is saved. In an upper time interval, maximum theoretically improvement is 97%, which is practically achieved by receiving two packets per day.

Because these results set energy saving benefits to any UWSN which introduces sleep times within its nodes, it motivated us to the development of this new AT-WU system with such lower consumptions to be especially used within also low-power acoustic modems.

2) Wake-up Power Consumption Analysis

In case of varying the wake-up circuit consumption due to design or applicative decisions (additional amplification, filtering, etc.), an interesting study consists of evaluating the impact that will represent to the whole embedded system.

Results will show if a wake-up system with certain power consumption is feasible in a specific scenario or not.

To get a wider perspective, two different inter-arrival time periods have been configured: one packet per minute and one packet per hour.

As observed in Fig. 17, one packet per minute saves 93% of energy. When power consumption of a wake-up system is about 100μW the whole system only wastes 10% of energy additional to the *optimal* solution.

In case of packets received every hour, wake-up system power consumption becomes significant. When a wake-up system dissipates 50μW, approximately 10% of energy is wasted compared to the *optimal* solution. However, this energy waste difference increases as long as the wake-up circuit consumption gets closer to node consumption in RX mode. At this moment, independently of the traffic, power consumption is equal and not upper to *idle* solution.

C. Small Craft Marina Experiments

The following experiments have been run in a real sea water scenario as a craft marina, shown in Fig. 18. Such a noisy environment represents an ideal scenario to evaluate WU system prototype.

1) Wake-up Detection Distance

The transmission distance reached depends on transmission power amplification. The ITACA modem has been tested with 12mW, 48mW, and 108mW. In October 2011, the modem reached 240 meters with 108mW in sea water.

Signal degradation at different distances can be observed in Fig. 19. Amplitude has been normalized via using the VGA. At 40m with maximum TX power (108 mW), the magnitude of noise can be observed. Although our measurement equipment [15] was not capable of detecting any signal over the noise level with longer distances, AT-WU still detected successfully incoming tones and patterns.

2) False Wake-up Detection Test

We wanted to determine if false wake-ups can occur in a noisy scenario. The AT-WU was configured to carry out only carrier frequency detection (without pattern recognition).

A node remained submerged during 24 hours and any false wake-up occurred during the whole experiment.

However, pattern recognition is still recommended to both facilitate extensive UWSN deployment and as an additional dependability mechanism. In future, the study will be extended with a correlation among existing oceans acoustic frequencies and low-cost piezoelectric resonance frequencies to determine which transducers are better to be adapted to the ITACA modem.

Fig. 18 Small Craft Marina Experimental Scenario (GPS: 39,562, -0.283)

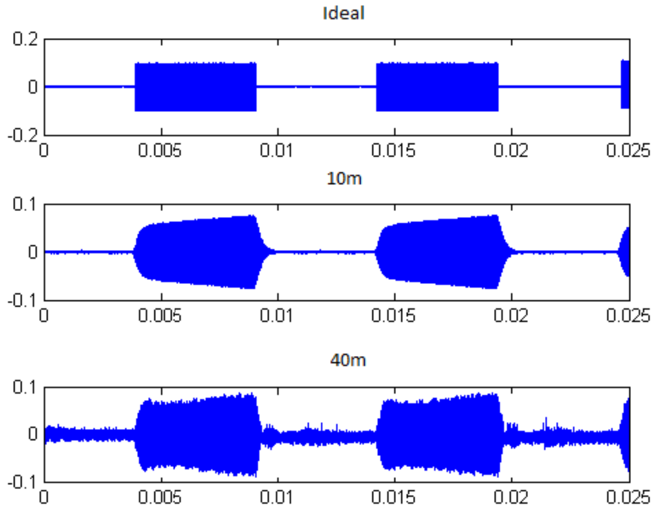

Fig. 19 OOK Received Signal in Small Craft Marina Test at Different Distances (Amplitude Scaled with a VGA)

VIII. CONCLUSIONS

This work presents an asynchronous Wake-Up acoustic system for Underwater Wireless Sensor Nodes which has been practically implemented and tested on sea waters.

The system includes specific hardware and operational configuration on the reception side, consuming within 8.1μW while it waits for wake-up external stimuli. To the best of our knowledge, this is the lowest consumption reported until now. The transmission of the Wake-Up signal does not need any specific circuit or variation on the modem architecture.

The Wake-Up system is able to react to an external acoustic stimulus in the form of simple carrier frequency detection or adding pattern recognition using OOK modulation. Besides, we have extended pattern detection concept to an optimized multiple pattern recognition system.

We have run several experimental tests in a small craft marina reporting detections at 240 meter with 108mW of transmission power.

Finally, an accurate model for Simulink suite of MatLab has been implemented and validated. This module will be very useful in future complex network simulations.

In conclusion, the work presented in this paper would help in the definition and evaluation of energy-efficient network communication policies based on asynchronous Wake-Up Medium Access Control.

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REFERENCES

[1] "M41T81: Serial Access Real-Time Clock with Alarms Data Sheet v.7,"

STMicroelectronics, Jun 03, 2005.

[2] "C8051F93x-C8051F92x: Single/Dual Battery, 0.9-3.6 V, 64/32 kB, smaRTClock, 10-Bit ADC MCU Data Sheet. Rev. 1.2.," Silicon Labs, May 2011.

[3] C. Schurgers, V. Tsiatsis, S. Ganeriwal and M. Srivastava, *Topology management for sensor networks: exploiting latency and density*, in Proc. of the 3rd ACM International Symposium on Mobile Ad Hoc Networking and Computing (MobiHoc), 2002.

[4] A.F. Harris III, M. Stojanovic and M. Zorzi, *When Underwater Acoustic Nodes Should Sleep With One Eye Open: Idle-time Power Management In Underwater Sensor Networks*, in Proc. Of the 1st ACM international workshop on Underwater networks 2006, pp 105-108.

[5] J. Wills, W. Ye and J. Heidemann, *Low-power acoustic modem for dense underwater sensor networks*, in Proc. of the 1st ACM international workshop on Underwater networks, ACM 2006.

[6] N. Pletcher, S. Gambini and J. M. Rabaey, *A 2GHz 52µW Wake-Up Receiver with -72dBm Sensitivity Using Uncertain-IF Architecture*, in IEEE ISSCC, 524-525 (2008).

[7] M.S. Durante, and S. Mahlknecht, *An ultra low power Wakeup Receiver for Wireless Sensor Nodes*, in Proc. of Third International Conference on Sensor Technologies and Applications, 167-170 (2009).

[8] J. Ansari, D. Pankin and P. Mähönen, *Radio-Triggered Wake-ups with Addressing Capabilities for Extremely Low Power Sensor Network Applications*, International Journal of Wireless Information Network 16 (3), 118-130 (2008).

[9] A. Sanchez, J. Aguilar, S. Blanc and J.J. Serrano, *RFID-based wake-up system for wireless sensor networks*, in Proc. SPIE 8067, 806708 (2011); doi:10.1117/12.887039.

[10] ns-3 simulator. http://www.nsnam.org

[11] A. Sanchez, S. Blanc, P. Yuste and J.J. Serrano, *A low cost and high efficient acoustic modem for underwater sensor networks*, in IEEE OCEANS 2011.

[12] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski and K. Ball, *The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms*, in Proc. of IEEE Oceans Conference 2005.

[13] R.A. Iltis, H. Lee, R. Kastner, D. Doonan, T. Fu, R. Moore and M. Chin, *An underwater acoustic telemetry modem for eco-sensing*, in Proc. of MTS/IEEE Oceans volume 5, 2005.

[14] G. Parsons, S. Peng and A. G. Dean, *Short paper: an ultrasonic communication system for biotelemetry in extremely shallow waters*, in Proc. of the third ACM international workshop on Underwater Networks, ACM 2008.

[15] "AS3933 – 3D Low Frequency Wakeup Receiver Data Sheet v1.0," Austria Microsystems, Jul 01, 2010.

[16] TDS 1012 Two Channel Digital Storage Oscilloscope. Tektronix.

[17] J. Llor, and M.P. Malumbres, *Underwater Wireless Sensor Networks: How Do Acoustic Propagation Models Impact the Performance of Higher-Level Protocols?* Sensors 2012, 12, 1312-1335.

[18] *MATLAB - The Language Of Technical Computing.* MathWorks. www.mathworks.com/products/matla.