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Ultra Low-Power Always-On Wake-Up by Pulse Pattern Adaptive Recognition for Long Term Biodiversity Monitoring

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Abstract—This paper presents a mixed analog-digital always-on ultra low-power wake-up based on pulse pattern analysis. It is used for triggering a high performance multi-channel recorder only when necessary. Its architecture makes the most of ultra-low power analog primitives coupled with an embedded digital low power system for fine tuning the pulse detector in order to maximise its efficiency. Such system allows long term biodiversity study, as most of the bioacoustic energy is pulsed. As an example, a case study demonstrates on real sperm whale biosonar the efficiency of our system. Architecture and features extraction using analog primitives are first detailed, followed by embedded digital implementation of the automatic gain control for the pulse detector. Always-on current consumption of this intelligent wake-up is $14\mu A$, with an area under the ROC curve equal to 75%. This allows an autonomy of 2 years on a single CR2032 battery cell.

Index Terms—Ultra Low-Power, Always-on Wake-up, Pattern Detection, Embedded Artificial Intelligence, Biosonar, pulse train.

I. INTRODUCTION

Every day, more than one hundred of animal species disappear in the world. Gathering a better knowledge on animals helps to protect them and biodiversity monitoring is a key for that. In this paper, we focus on acoustic monitoring of animals emitting sound pulses, bursts or frequency chirps. Many animals enters this category, from very small ones such as insects, but also as birds that emits trains of voiced pulses. Biosonar of mammals are perfect examples of such kind of emission with trains of clicks. This is illustrated with bats, but also marine mammals. We also find in marine mammals low frequency voiced pulse trains, the strongest are the 15 Hz pulses of the blue whale. Thus, most of the biomass emits trains of pulses, and required monitoring programs to protect biodiversity is lacking of low power and low cost system. We first present a case study on real signal, then we present our method, followed by metrics of its efficiency.

II. A CASE STUDY : A BIOSONAR OF A MARINE MAMMAL

In this paper, we will illustrate our work on a cryptic species, swimming in abysses 85% of its time, the sperm whale. This latter has been chosen as our case study for this

paper, but results could also be applied to other species with minor adaptations. Among the endangered species, sperm whales and other cetaceans have been categorized as vulnerable, due to anthropogenic activities such as transportation or fishing [1]. These ones, creating pollution, noise and global warming, are leading to a slow decay of these populations [2]. Moreover, sometimes they also lead to sudden death of cetacean due to collision with boats [3]. Thus, monitoring them is a major concern in order to better know them, but also to detect a probability of collision in advance in order to avoid it.

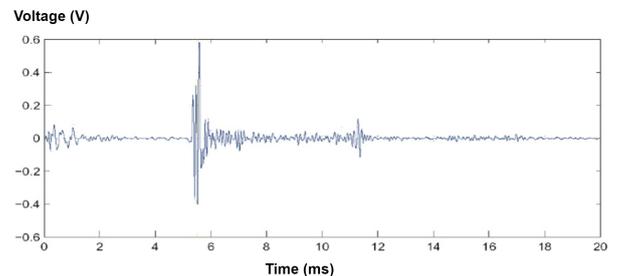


Fig. 1. Cetacean click signal.

Sperm whales are using echo-location for orientation and prey localization. Signals emitted are composed by sequences of *clicks* named *codas* [4]–[6]. Each click is very short as shown Fig. 1 and is composed by a direct and a reflected burst emitted by pneumatic compression [7], [8] (Fig. 2). Depending on the relative orientation of the animal and the receiver, these bursts can be received simultaneously or at successive instants. Thus, detection algorithms have to be compliant with these variations.

Clicks are composed by a burst with a frequency spectrum going from $6kHz$ to $20kHz$ (Fig. 6) [9]–[12]. Each click is separated from the next one by a time interval $T_{InterClick} \in [100ms; 1s]$.

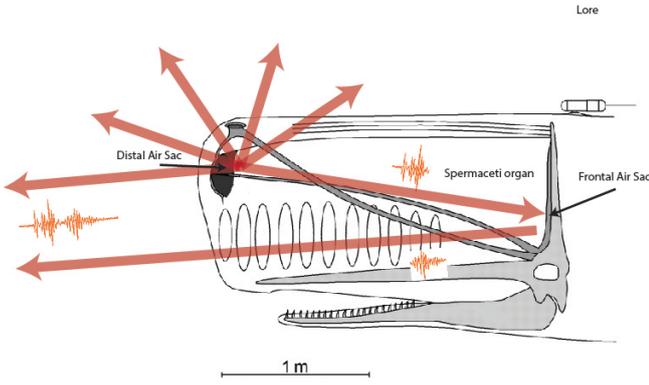


Fig. 2. Sperm Whale emission principle : a burst is emitted by the distal air sac, propagated by the spermaceti organ and reflected by the frontal air sac.

Cetaceans monitoring is complex because these mammals are spending most of their life in deep water, going down to 2000 m under sea-level and moving on long distances. Moreover, due to the sparsity of these animals, they are rarely present in a given area. Consequently, a lot of memory storage and energy is spent in a useless way when using always-on recording systems for monitoring them. This issue is reinforced by the necessity of having high frequency recordings with multiple hydrophones in order to be able to reconstruct precisely their trajectories as in [12]. This means that always-on cetacean recorders must have large batteries and storage capacities for being able to record sounds from multiple hydrophones for a long time. This is a strong constraint has many consequences : bio-environmental equipment is heavy, expensive, and difficult to install and maintain. Having smaller recorders with an increased autonomy would be a major step toward a more precise and complete knowledge of these sea giants and biodiversity in general.

III. DEFINITION OF OUR ULP MONITORING SYSTEM

In this paper, a solution for reducing recorder and storage size and power consumption is proposed, based on the assumption that most of the time, recording is not necessary because animals are not present. It relies on a always-on ultra-low power pulse detector triggering a smart high performance acoustic recorder. It makes the most of three types of circuits that can be used for artificial intelligence implementations, each one having a different magnitude of power consumption as shown in Fig. 3 :

- An ultra low power mix analog-digital acoustic wake-up system : having a power consumption of $40\mu W$, it aims at detecting abnormal acoustic event transmitted to a micro-controller. It can be classified as an ultra low-power wake-up [13]–[15]. However, unlike in [16] where only analog parts are used or in [17] where a micro-controller is used without external analog circuitry, it makes the most of the combination of ultra-low power

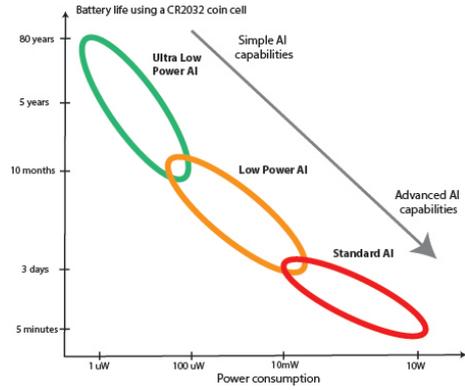


Fig. 3. Different types of embedded AI according to their power consumption

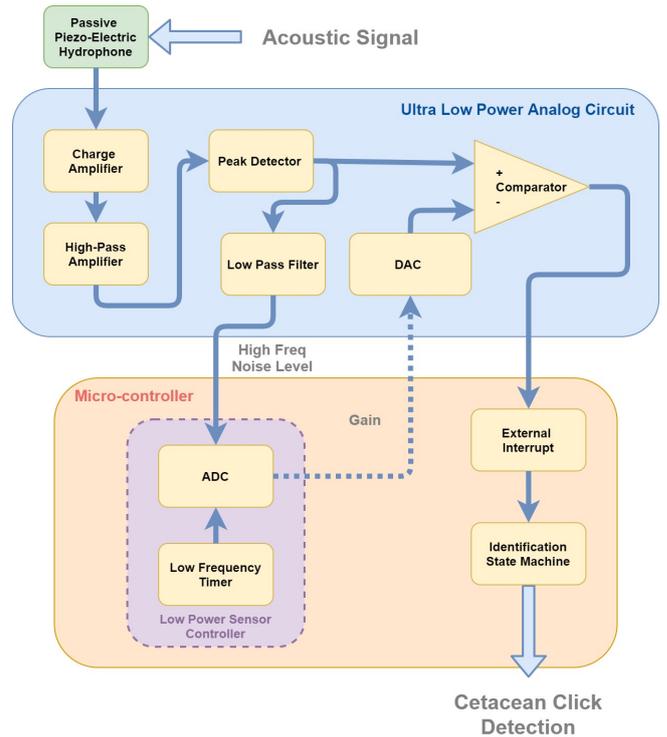


Fig. 4. Sperm Whales detector block diagram.

analog circuits and the *sensor controller* of a low-power micro-controller.

- A low power micro-controller is used for adding flexibility by implementing low power advanced features in the detector. In this paper, one of these features is an algorithm tuning dynamically click detection sensitivity according to the average environmental noise as shown in Section V.
- A higher power 24 bits 4-channels recorder, able to compute deep-learning signal analysis using an embedded GPU, is triggered by the clickdetector. Recordings have an excellent quality with a high

sampling rate with several channels, but they consume a lot of energy (more than $1.2W$). Its high temporal resolution (512 ksp/s) and synchronization between channels allows further processing of the signal is necessary as it is a key for computing trajectories of the cetaceans and for identifying them reliably. This recorder is started only when clicks have been validated by the detector, reducing drastically its average power consumption compared to an always on recorder. Active less than 0.05% of the time in real conditions (due to the sparsity of sperm-whales), it extends the battery life of the recorder by a factor 2000 reducing its average power consumption to less than $1mW$. This allows a drastic battery and overall size reduction, easing its installation and maintenance while reducing its cost. This high resolution recorder, built by SMIoT [18] is named *Qualilife HighBlue* but is not on the scope of this paper.

Ultra low power part of the wake-up system is presented in this paper as well as the dynamic embedded tuning algorithm. In section IV, the ultra low power part of the circuit wake-up is described. In section V, click detection algorithms optimizations are presented. In section VI, results are discussed.

IV. ULTRA LOW-POWER ALWAYS-ON WAKE-UP ARCHITECTURE

Architecture proposed for the mixed analogical and digital wake-up on cetacean clicks is presented in Fig.4. It relies on the following ultra low power circuits :

- Passive piezo-electric of frequency ranges from 1 Hz to 50 kHz with a charge amplifier in output.
- Charge amplifier : it is an integrator with very high input impedance, converting charge into voltage. Charge amplifier uses a charge in input and multiplies it by the inverse of the capacitance in the feedback path, converting the charge into a voltage with an adjustable gain C_1 as shown on Fig. 6. Without considering the additional resistor :

$$V_{Out} = \frac{1}{C_1} \int \frac{dQ}{dt}$$

Additional resistor R_1 forms a low-pass filter with C_1 for slowly *resetting* the output voltage when there is no input signal. Power consumption of this block is the one of a single op-amp : $0.9\mu A$.

- High-pass amplifier : removes the low frequency sea noise from the signal while amplifying it. Considering cetacean clicks frequencies are above $8kHz$, a high-pass filter having this cut-off frequency has been chosen. This active filter also amplifies the signal by a factor 10 using an ultra low power op-amp (Microchip *MCP6141*). Power consumption of this block is $1\mu A$.

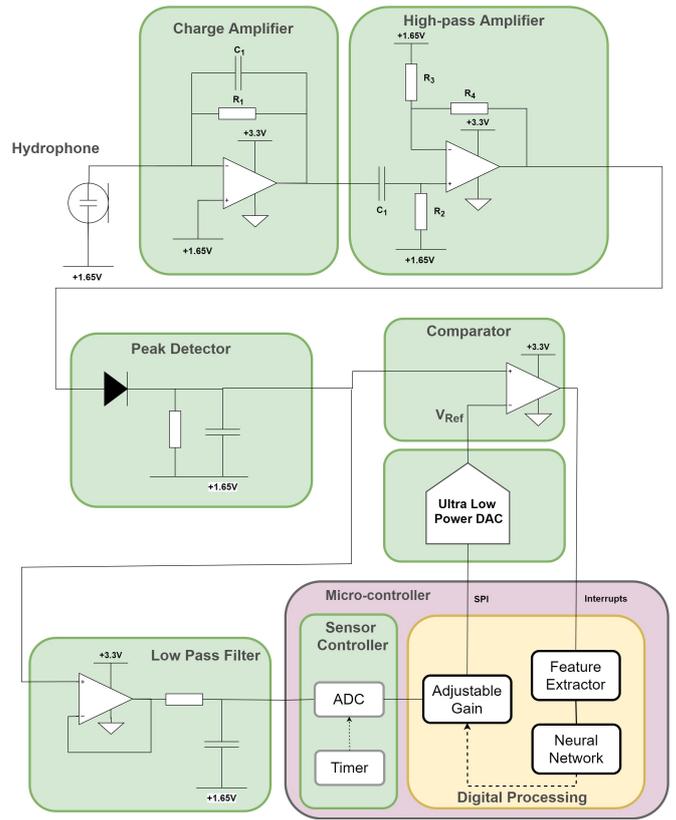


Fig. 5. Electronic circuit of the always-on wake-up. Ultra low power parts are in green, low power digital parts are in orange. Voltage regulator and $1.65V$ reference are not presented.

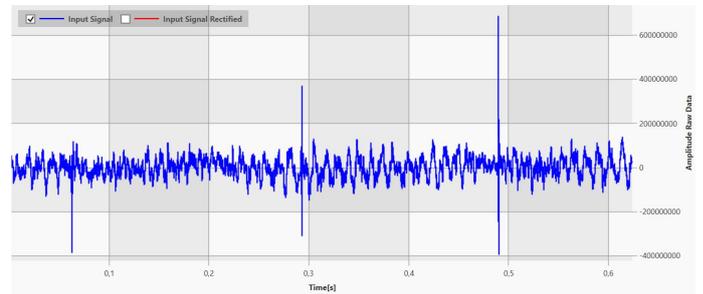


Fig. 6. Cetacean clicks signal in output of the charge amplifier. Three clicks are present in the signal as well as sea noise

- Peak Detector : combining a diode and a low pass filter, it extracts the envelope of a click. This is necessary in order to gather multiples peaks of a cetacean click into one single envelope, even when click reverberations are present as shown in Fig. 7. Power consumption of this passive block is null.
- Low pass filter : output of the peak detector is filtered by a (0.1 Hz) low-pass filter. In case of a stationary high frequency noise, this output average value V_{Noise} is equal to the noise amplitude whereas in case of an isolated click output average value is equal to the reference level

1.65V. This filter gives a good approximation of the high frequency sea noise level, that will be used for tuning the detection triggering levels of the comparator. A follower op-amp has to be added between the peak detector and the low-pass filter, consuming 600nA.

- Comparator : used for comparing the input signal to a reference value V_{REF} related to the sea noise level in order to detect clicks. Reference value generation is detailed in the corresponding item. A ultra low power analog comparator having a power consumption of 320nA is used.
- Reference value V_{Ref} generation : this feature is very important. A too small V_{Ref} would trigger the comparator too often and generate false alarms, whereas a too high V_{Ref} would lead to miss smallest clicks happening when a cetacean is far from the detector. Thus, an analog solution based on a fixed gain amplifier is not a reliable solution as it cannot be tuned. Instead of that, a mix digital-analog ultra low-power solution is used, relying on the *sensor controller* of the CC2652 micro-controller. *Sensor controller* embeds ultra low-power parts that can be used stand-alone without activating the micro-controller core. In our wake-up, a low frequency timer (0.1Hz) triggering an ADC is used for sampling the low-pass filter output value.

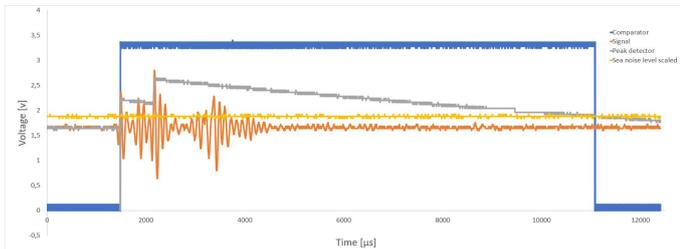


Fig. 7. Cetacean clicks signal with ultra-low power processing, acquired on real signals. Input signal high-pass filtered is in orange, V_{Ref} is in yellow, click envelope is in grey and output of the comparator is in blue.

Sea noise estimation is used for digitally adjusting a gain converted into an analog value V_{Ref} using a SPI ultra low power DAC. V_{Ref} is equal to :

$$V_{Ref} = K_1 V_{Noise} + K_2 \quad (1)$$

where K_1 and K_2 are fixed constants. Power consumption of the *sensor controller* used for reference value generation is 4μA.

- Digital-to-analog converter : a LTC1662 DAC is used for converting the reference value transmitted by the *sensor controller* in SPI to an analog value. Its power consumption is 1.5 μA.

- Voltage regulators : a 3.3V supply voltage value has been chosen. Powered by a single Li-Ion 3.7V cell, a Microchip MCP1810 linear voltage regulator has been chosen, having a power consumption equal to 300nA. Reducing input voltage to 1.8V would be a good option and will be done in a further work.
- Voltage reference : a single 3.3V supply is used, requiring to generate a virtual 1.65V ground voltage. This is done using a 1.65V power supply having a current consumption of 0.3 μA.

Table I shows power consumptions of each circuit used in the ultra-low power part of the click detector. Measurements have been done using a custom analog test and power measurement board having different power supplies for each analog module as shown on Fig. 8.

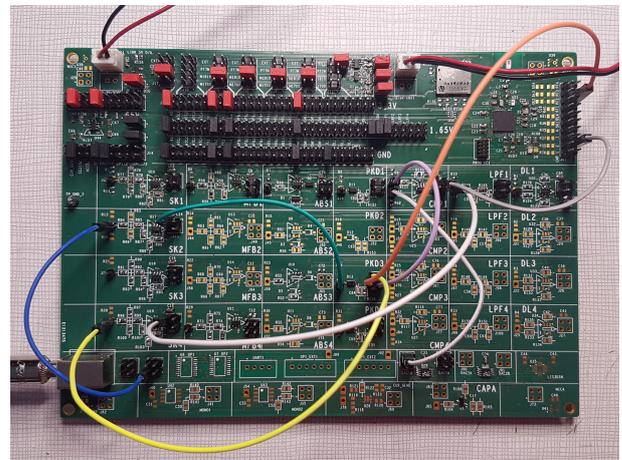


Fig. 8. Analog test and power measurement board

This leads to an aggregated power consumption equal to 9.5μA.

Circuit	Consumption
Charge Amplifier	1.0μA
High-pass Amplifier	4.0μA
Peak Detector	-
Sea noise Low frequency Low-pass Filter	0.6μA
DAC	1.5μA
Comparator	0.3μA
3.3V voltage regulator	0.3μA
1.65V voltage reference	0.3μA
Sensor Controller using a 10 Hz timer	4.5μA
Complete ultra-low power hardware	12.5μA

TABLE I
ALWAYS-ON ULTRA-LOW POWER ANALOG CIRCUITS POWER CONSUMPTION.

V. DETECTION AND OPTIMISATION

An important feature of the proposed ultra-low power cetacean detector is the ability to automatically tune the comparator reference value V_{Ref} described at Eq. 1 depending on the sea ambient noise. This equation uses 2 fixed hyper-parameters K_1 and K_2 that have to be optimised in order to maximise classification accuracy.

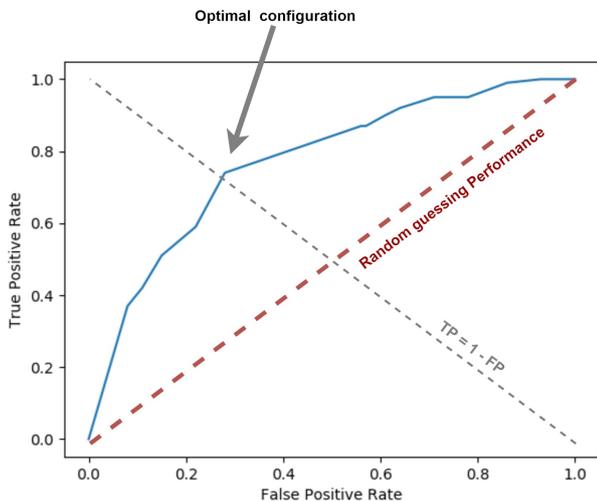


Fig. 9. ROC curves for different values of K_1 parameter.

Performance is evaluated using a test set of 100 recordings taken at random in a labelled database composed of samples from SPHYRNA mission that have been labelled using highly reliable automated high power deep learning algorithms for cetacean detection [12].

For evaluating the performance of the classification embedded system, Receiver Operating Characteristic (ROC) curve and average precision (AP) are used as proposed in [19]. ROC curve is presented in Fig. 9 : area under the curve (AUC) is equal to 75%. An optimal configuration corresponds to $K_1 = 4.3$ and $K_2 = 0.25V$.

This is an excellent result considering system power consumption is only $12.5\mu A$. Moreover, it is important to note that the database is mainly focused on sperm whales and motor boats but has very few samples of silent sea. Consequently, detecting clicks on this database is much more difficult than it would be in real conditions with a frequently quiet sea.

VI. RESULTS AND DISCUSSION

The proposed mixed analog-digital always-on ultra low power wake-up for cetacean click detection can be classified as an ultra low power artificial intelligence application such as presented in Section I. Its overall measured power consumption is $12.5\mu A$ in real conditions. Tested on a labelled dataset that is more difficult than real conditions, its area under the receiver operating characteristic (ROC) curve is equal to 75%.

A. Further work

Proposed click detector is dynamically tuned taking into account the high frequency noise level. However, is it possible to improve the detection by adding some expert rules to the classification embedded system. Among them are well-known information about clicks and codas [8], such as the inter-click interval and the click duration. These artificial intelligence expert rules can be implemented in the sensor controller using state-machines. This will be part of a further work.

VII. CONCLUSION

In this paper, a mixed analog-digital always-on ultra low-power wake-up based on pulse pattern analysis is presented. It is used for triggering a high performance multi-channel recorder only when necessary. Its architecture makes the most of ultra-low power analog primitives coupled with an embedded digital low power system for fine tuning the pulse detector in order to maximise its efficiency. An application to sperm-whales click detection is proposed as a case study. Architecture and features extraction using analog primitives are first detailed, followed by embedded digital implementation of the automatic gain control for the pulse detector. Always-on current consumption of this intelligent wake-up is $14\mu A$, with an accuracy of detection equal to 75%. This allows an autonomy of 2 years on a single CR2032 battery cell. More complex pattern analyses are in current work based on same principle, merging frequency filter bank and heterogeneous temporal features analysis. We thus open a framework for low power online species identifications, from cetacean to bat biosonar, birds to insects and amphibians, but also anthropophonic sources.

Beyond its use in biodiversity monitoring, this type of wake-up based on pulse pattern analysis can be seen as an example of implementation of feature extraction for ultra low power artificial intelligence. This is key for the development of edge computing for the Internet Of Things (IoT).

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