An Aquatic Wireless Biosensor for Electric Organ Discharge with an Integrated Analog Front End

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Abstract—This paper presents a novel wireless underwater data acquisition system for sensing Electric Organ Discharge (EOD) signals generated from the weakly electric fish *S. macrurus*. Variation in frequency and amplitude of the EOD signals are of interest by biologists to study behavioral and environmental effects on electric organ cells. In order to record the EOD signals, a miniature wearable wireless sensing system is designed for the target fish. The system consists of a custom-designed integrated Analog Front-End (AFE), an ATmega328p microcontroller unit (MCU) and a wireless transmitter (TX), as well as a battery with a power management module. In order to save TX power, the wireless sensor only transmits the calculated frequency and amplitude information of the EOD data to perform further analysis. A wearable waterproof backpack for the fish is designed to house the wireless sensor and battery. The overall system has been successfully tested in a clinical experiment with the weakly electric fish. The AFE integrated circuit, which includes a novel rail-to-rail dynamic comparator, is fabricated in a 0.18-µm CMOS process. The total area of the core circuit is 1.0 mm². The LNPA achieved a Noise Efficiency Factor (NEF) of 1.8. The AFE power consumption is 2.2 µW from a single +1.8 V supply, whereas the overall system power consumption is 15 mW. The proposed gain-feedback control structure for frequency and amplitude measurements saves the transmitter data rate by 3,756 times compared with sending the raw data.

Index Terms—Analog Front-End (AFE), Electric Organ Discharge (EOD), Underwater Wireless Biosensor, Dynamic Comparator, Rail-to-rail Comparator.

I. INTRODUCTION

This paper introduces a novel sensor structure designed for a wireless underwater biosensor. In recent years, wireless sensor and data acquisition systems have been widely used in biological research applications [1]–[8]. The primary goal of such systems is to sense and analyze biological signals while the subject animal can move freely. To achieve this goal, the wireless biosensor system generally consists of an Analog Front-End (AFE), which includes amplifiers and an Analog-to-Digital Converter (ADC), a Digital Signal Processing (DSP) module, and a wireless transceiver or transmitter (TX). The design challenges of such systems include low-power consumption of the overall system, low-noise design in the AFE, hardware-friendly DSP algorithms, and the miniaturized physical size and weight of the sensor device. Besides these typical design considerations, extra design considerations may be included in special applications, such as deploying the sensor in an aquatic environment, as illustrated in Fig. 1.

Aquatic wireless sensors [9]–[13] play an important role in facilitating non-invasive long-term studies of underwater biological processes and animal behaviors. One such behavior of great interest to biologists is the production of electrical fields by electric fish. The long-tailed knife-fish *Sternoptyx macrurus*, like all electric fish, produces an electric organ discharge (EOD) that is essential for navigation, communication, and mating [14]. The EOD of *S. macrurus* is the output by the muscle-derived electrogentic cells called electrocytes, which are activated continuously throughout the life of the animal [14], [15]. Characterization of the EOD of *S. macrurus* has been largely studied with fish in captivity. However, relatively little is known about environmental factors, such as light intensity, temperature, and chemistry of aquaria water, that may affect the fish’s EOD during a 24-hr period or longer. Moreover, functional studies on the temporal recovery of the EOD during the transdifferentiation of skeletal muscle cells into electrocytes during tail regeneration after amputation is not known [15].

Currently, biologists still lack an understanding of how nerve-dependent electrical activity regulates the regeneration of the striated muscle cell phenotype. This is a fundamental problem in biology with high implications to neuro-muscular repair and restoration following injury or disease – a research area in muscle biology and regeneration fields that is understudied. For instance, the adult *S. macrurus* regenerates its tail after amputation through formation of a blastema beneath the epidermis at the wound site. Regeneration of all tissue types, including the spinal cord, skeleton, dermis, skeletal muscle and EO can occur after repetitive tail amputations. However, full restoration of all amputated muscle fibers and the complete transdifferentiation of muscle cells into EO cells does not take place in the absence of electrical activity. So in vivo studies merit the pursuit of discovering the mechanisms that link...
electrical activity to regulation of distinct skeletal muscle biology in this highly regenerative aquatic vertebrate. However, this requires instrumentation that can manipulate and record electrical stimulation during regeneration after tail amputation. To date, there is no experimental hardware for underwater chronic electrical stimulation and recording. Therefore, the capability to record EOD amplitude and frequency under different experimental conditions while the fish moves freely would greatly enrich ongoing cellular and molecular studies.

To meet such requirements, aquatic sensors have been designed and implemented to collect data for biological studies. In [16], a wireless sensing framework was designed and implemented to record the EOD signal using off-the-shelf-components. Due to the size and power consumption of the sensor, the device can only be deployed near the fish nest, which limits the accuracy of sensing and suffers from signal loss if and when the fish swims away from the nest. The amplitude measurement is also not reliable since the distance between the sensor and fish constantly varies. In [17], compressive sensing was applied using the senor in [16]. In [18], a stimulator circuit was built for chronic in vivo stimulation with a wearable backpack for the fish. Though the subject fish can move freely with the stimulator backpack, sensing the electric field relies on the sensor in the fish nest [16]. In these aquatic prototypes, major design challenges beyond a typical biosensor include the waterproof capsule for the sensor, underwater noise, wireless signal attenuation, and ground signal offset.

To solve the above problems, in this paper, we designed and tested an aquatic wireless biosensor, as shown in Fig. 1. The major innovations and contributions of the work include: (1) the prototype design and implementation of the first complete aquatic wireless biosensor in a clinical environment that remotely measures EOD frequency and amplitude for biology studies, (2) the system design of gain-feedback control between the AFE circuit and microcontroller to achieve reliable frequency measurement while calculating the amplitude, which saves wireless power by avoiding transmitting the raw waveform, and (3) a rail-to-rail dynamic clocked comparator with zero static power consumption. This design can be used as a reference design for other aquatic wireless biosensors. The paper is organized as follows: Section II introduces system design considerations. Section III describes circuit-level and system-level implementation details. Section IV presents the experimental setup and results. Section V provides discussion and conclusion.

II. SYSTEM DESIGN CONSIDERATIONS

S. macrurus is a weakly electric fish that generates an electric organ discharge (EOD) using synchronized discharges of spinal electromotoneurons via activation of their target electrocytes, which make up the electric organ. The EOD is the stereotypical electric organ pulse generated by electric fishes that have a species-specific frequency and rhythm. The EOD is generated in the pacemaker neurons located in the brainstem of the fish and relayed to the electric organ to generate the electrical field around the fish. The EOD signal has an amplitude of 1-2 mV when measured by near-field electrodes placed within 5 cm of the fish. The primary frequency of the EOD signal ranges between 50-200 Hz [14]. The frequency and amplitude of the EOD signal vary between individual fish and are affected by behavioral and environmental factors. Therefore, in order to study the relationship between the EOD signal and other biology topics, scientists are expecting wearable biosensors that can be attached to the fish and wirelessly transmit the EOD signal’s amplitude and primary frequency while the subject fish moves freely. Design considerations of this automatic data acquisition system, therefore, include accuracy, weight, size, and battery lifetime of the wireless sensor, as well as reliability and bio-compatibility.

The system building blocks and experimental setup are illustrated in Fig. 2. This system consists of the non-invasive wireless sensor attached to the subject fish and a host computer with a wireless receiver collecting the sensed data. The sensor contains the custom-designed AFE chip, an 8-bit ATmega328p microcontroller unit (MCU), a radio frequency (RF) transmitter (TX), and two low-dropout voltage regulators (LDOs). The whole system is powered by a rechargeable lithium polymer (LiPo) battery with an output voltage in the range of 3.7-4.2 V. LDOs step down the battery output voltage to clean supplies of 1.8 V and 3.0 V. 1.8 V is used to power the AFE, while 3 V is used to power the MCU and the TX module. All the above circuits and battery are placed on a 1.5" × 1" printed circuit board (PCB) and encapsulated in a plastic 4" × 2" waterproof case. The EOD sensing probe electrodes are placed near the tail of the fish to sense the near-field electric field.

The system measures the EOD frequency and amplitude using zero-cross detection and a gain-feedback control method. While in operation, the AFE continuously senses the analog EOD signal and performs analog amplification, frequency filtering, DC offset cancellation, and analog-to-digital conversion. The MCU receives the digital data from the AFE and measures the frequency of the EOD signal using a zero-crossing detection algorithm: the MCU monitors the ADC output and compares it with a pre-defined threshold value during a certain time period, and counts the number of times the ADC output crosses that pre-defined threshold value. Although this method is simple and saves computing power compared to performing a Fast Fourier Transform, it is susceptible to input signal noise. Therefore, in order to better implement this method, the ADC input signal should maintain a high amplitude, i.e., a peak-to-peak swing that is nearly rail-to-rail. This can be achieved by increasing the gain in the pre-amplifier. Nevertheless, if the gain of the pre-amplifier is too high, the ADC input signal would saturate and then the amplitude of the subject EOD signal cannot be accurately measured. To solve this problem, in this design we added a variable gain amplifier (VGA) stage between the pre-amplifier and the ADC. The gain of the VGA is controlled by the MCU.
via digital gain-feedback control logic. The MCU monitors the ADC output data and increases the gain of the VGA if the ADC input amplitude decreases, or vice versa. This function guarantees that the ADC input amplitude is nearly rail-to-rail, but not saturated. By using this method, the frequency of the signal can be reliably measured using the zero-crossing method and without saturating the ADC. The amplitude of the EOD signal is calculated from both the VGA gain and the ADC output.

The system transmits both the frequency and amplitude data using a short-range wireless module. The MCU first combines the data into a serial format and then organizes the data into packets. The wireless TX module transmits the data packets using Amplitude-Shift-Keying (ASK). Finally, the ASK receiver decodes the data and saves it on the computer for further analysis. The system only transmits frequency and amplitude data instead of the raw EOD waveform in order to reduce the data rate and, hence, the power of the RF block. Details of each circuit building block are described in the following section.

### III. SENSOR ARCHITECTURE AND IMPLEMENTATION

The proposed EOD sensor is based on our previous work which employed discrete off-the-shelf components, as published in [16]. In this work, we update the design using an integrated AFE chip and the gain-feedback control architecture. Fig. 3 shows the proposed AFE and gain-feedback control building blocks. The AFE includes a Low-Noise Pre-Amplifier (LNPA), followed by a Variable Gain Amplifier (VGA) and an 8-bit Successive Approximation Register Analog-to-Digital Converter (SAR ADC) that incorporates a novel rail-to-rail dynamic comparator. The microcontroller takes data from the ADC and measures the amplitude and the primary frequency of the EOD signal. The microcontroller also adjusts the gain of the VGA based on the instance amplitude of the EOD signal. The calculated frequency and amplitude data are then sent wirelessly by the transmitter unit. The following subsections detail the circuit and system level design and implementation.

#### A. Low-Noise Pre-Amplifier (LNPA)

The first stage of the integrated AFE chip is the Low-Noise Pre-Amplifier (LNPA). The overall design goal of the LNPA is to optimize trade-offs between gain, bandwidth, noise, and power consumption for the target EOD signal. The design is based on [19] with modified parameters for a 0.18-µm CMOS process. The schematic of the LNPA is shown in Fig. 4. Due to the noisy aquatic environment, the LNPA adopts a fully-differential design to improve the Common-Mode Rejection Ratio (CMRR) and Power Supply Rejection Ratio (PSRR). Fully-differential design is particularly important with low supply voltages, as the signal swing is effectively doubled. Large DC offsets from the electrode-tissue interface are rejected by AC coupling the input signal through input capacitor $C_{1N}$. The input-referred noise of the LNPA is approximately equal to the input-referred noise of operational amplifier $A_1$. The gain of the LNPA is set to 100. Considering the expected frequency range of EOD signals (50-200 Hz), the low cut-off frequency is set to 10 Hz and the high cut-off frequency is set to 2 kHz.

#### B. Variable Gain Amplifier (VGA)

A variable gain amplifier adds robustness to the AFE by increasing its dynamic range. Fig. 5 shows the schematic of the Variable Gain Amplifier (VGA), which consists of a fully-differential amplifier in a closed-loop configuration. The architecture is similar to that used in the LNPA of Fig. 4; key differences are the op-amp uses an NMOS input differential pair and the input capacitors and compensation capacitors are programmable.
The midband gain of the VGA is $C_{IN}/C_{FB}$, where $C_{FB}$ is fixed and equal to 500 pF and $C_{IN}$ is implemented as a binary-weighted capacitor bank from 500 pF to 32 pF, in order to adjust the VGA gain from 0 dB to 36 dB in steps of 6 dB, which corresponds to a factor of 2. The main idea of having a variable input capacitor instead of variable feedback capacitor is to maintain a constant low cut-off frequency. The input capacitor of the VGA blocks any DC offsets generated at the output of the LNPA. The op-amp used in the VGA is a two-stage Miller-compensated op-amp. This topology is chosen because of its simplicity and ability to operate at low voltage supplies with a wide output swing. The transistor sizes and other design values for the LNPA and VGA are summarized in Table I.

![Fig. 5. Variable Gain Amplifier (VGA) with digital select lines $S_1 - S_7$.](image)

![Fig. 6. Proposed rail-to-rail dynamic comparator.](image)

**TABLE I**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LNPA ($A_1$)</th>
<th>VGA ($A_2$)</th>
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<td>$M_{1,2}$ [$\mu m/\mu m$]</td>
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<tr>
<td>$M_{16-20}$ [$\mu m/\mu m$]</td>
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<tr>
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<td>50</td>
<td>0.5–32</td>
</tr>
<tr>
<td>$C_{PE}$ [pF]</td>
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<td>0.5</td>
</tr>
<tr>
<td>$C_{C}$ [pF]</td>
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<tr>
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<td>1</td>
</tr>
<tr>
<td>$I_B$ [nA]</td>
<td>30</td>
<td>80</td>
</tr>
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</table>

**C. 8-bit Successive Approximation Register (SAR) ADC**

After amplifying and conditioning an input noisy signal from the fish through the LNPA and VGA, it is digitized by an Analog-to-Digital Converter (ADC). This conversion helps in further analysis of the EOD signal, as digital data is less susceptible to external noise. The Successive Approximation Register (SAR) ADC is preferred over other ADC architectures in this particular low-speed application because of its moderate resolution and good power efficiency.

The proposed SAR ADC is based on the design in [20], with modifications made in the control logic and comparator.

A novel rail-to-rail dynamic comparator helps achieve zero static power in the ADC. For this application, 8-bit resolution and 10 kHz sampling rate are selected.

**D. Rail-to-Rail Dynamic Comparator**

Fig. 6 shows the proposed rail-to-rail dynamic comparator that was designed with two main features: 1) rail-to-rail input range and 2) fully dynamic operation, resulting in no static power loss. The inputs to the comparator are nodes $V_{INP}$ and $V_{INN}$, which are the sampled outputs of the VGA and which are also attached to the DAC outputs of the binary-weighted capacitor arrays. Since 1 LSB is equal to 1.8 V/255, the DAC output voltage of a conventional SAR ADC can go as low as 7 mV and as high as 1.793 V. As such, a rail-to-rail comparator is desirable in a conventional SAR ADC architecture. The proposed design is based on the current-controlled latch sense amplifier of [21], which was analyzed and optimized in [22]. More recently, this sense amplifier has been adapted for low supply voltage in [23] and reduced delay in [24]. In our work, a low-power sense latch originally intended for high-speed SRAM is modified to achieve rail-to-rail input range in a low-speed bio-sensor application.

As shown in Fig. 6, rail-to-rail input common-mode range is achieved using parallel NMOS and PMOS input differential stages. The NMOS and PMOS structures are complementary with inputs $V_{INP}$ and $V_{INN}$ and outputs $V_{OP,CMP}$ and $V_{ON,CMP}$ tied across each half of the circuit. The top half of the comparator with the NMOS differential pair and NAND SR-latch operates when the input common-mode voltage is higher than the NMOS threshold voltage. The bottom half of the comparator with the PMOS differential pair and NOR SR-latch comes into the picture when the input common-mode voltage is below $V_{DD}$ by the PMOS threshold voltage. For inputs near $V_{DD}/2$, both structures operate in parallel.
Referring to the top half of Fig. 6, when input $CLK_C$ is low, the comparator is reset and nodes $A$ and $B$ are both set to $V_{DD}$. In this state, the outputs of the NAND SR-latch $V_{O,P,CMP}$ and $V_{O,N,CMP}$ are in the hold state, that is, they are holding the value of the previous comparison. In complementary fashion, referring to the bottom half of Fig. 6, when $CLK_C$ is high, nodes $D$ and $C$ are reset to 0 V, placing the outputs of the NOR SR-latch in the hold state. Now, at the rising edge of $CLK_C$, let us assume that $V_{INP}$ is greater than $V_{INN}$. In that case, in the top half of the circuit, node $A$ goes low, pulling $V_{O,P,CMP}$ to $V_{DD}$ through transistor $M_{16}$ and, through feedback transistor $M_{11}$, $V_{O,N,CMP}$ is pulled to $V_{SS}$. Similarly, in the bottom half of the circuit, at the falling edge of $CLK_C$, node $D$ goes high, pulling $V_{O,N,CMP}$ to $V_{SS}$ through transistor $M_{29}$ and, through feedback transistor $M_{32}$, $V_{O,P,CMP}$ is pulled to $V_{DD}$.

In order to prevent contention current in the case that one differential pair makes a decision faster than the other, feedforward transistors $M_{12}$, $M_{16}$, $M_{29}$ and $M_{33}$ are sized with multiplicity $(m)$ equal to three. Suppose that $V_{INP}$ is greater than $V_{INN}$, but that the input common-mode voltage is close to $V_{DD}$, such that the NMOS differential pair makes a fast decision and the PMOS differential pair makes no decision at all. In this case, after the rising edge of $CLK_C$, node $A$ goes low quickly, whereas node $D$ remains in the reset state. Node $A$ going low creates the possibility of contention current between transistors $M_{16}$ and $M_{34}$, if we further assume that output $V_{ON}$ was being held from the last comparison in the high state. By oversizing transistor $M_{16}$, $V_{OP}$ is pulled high through $M_{16}$ and, via feedback transistors $M_{11}$ and $M_{30}$, $V_{ON}$ is pulled low.

A zero-static power comparator with rail-to-rail input range has been proposed here for a conventional SAR ADC. In addition, it would find application as a discrete-time pulse-width modulator, a discrete-time envelope tracking converter, and a general-purpose input block. However, the SAR ADC architecture of [20] has a comparator input common-mode range that begins at $V_{DD}/2$ and monotonically decreases to 0 V. For this architecture, a PMOS-input StrongARM latch would have been sufficient [25]. Although the proposed rail-to-rail dynamic comparator is not optimum in terms of system area and power, it operates effectively and serves as a test circuit for future optimized architectures of the integrated EOD sensor.

### E. Microcontroller and Wireless Interface

The ATmega328p microcontroller unit (MCU) is used to adjust the gain-feedback control signal to the VGA, compute amplitude and frequency, and organize the data into packets for the wireless transmitter. To each data packet, preamble bits “10101010” are added, which translate to HEX 0xA5. The preamble helps the receiver identify the beginning of a data packet. The system applies off-the-shelf radio transmitter modules QAM-TX2 and receiver QAM-RX2 as the radio interface. At the receiver side, the QAM-RX2 module is connected to a laptop through USB. The serial output received from the UART is recorded on the laptop, which runs a Python script to read the serial data from the USB. An error detection algorithm is implemented in the laptop using the checksum of the data packet. If the checksum doesn’t match, or the detected frequency is out of a pre-defined range, the system abandons the packet and displays an error message. Otherwise, the Python script records the amplitude, frequency, and timing information to a text file.

In this EOD measurement application, since the frequency and amplitude do not change suddenly, we adopted an error detection algorithm, which includes both the checksum and a pre-defined frequency range, to abandon faulty data. This error detection algorithm does not affect the experiment if the error rate of the packet is not too high. In our experiment, the error rate of the packet is approximately 4% of the total readings, which does not affect recordings of frequency and amplitude.

The gain-feedback control in this design saves system power by reducing the transmitter throughput. This is because, using the gain-feedback method, the MCU can calculate the frequency and amplitude of the EOD signal even when the EOD signal has a small amplitude. In this design, the frequency and amplitude of the signal are transmitted every three seconds. Within each data packet, there are only 64 bits: 32 bits for header synchronization, 16 bits for data, followed by the 8-bit checksum, then another 8 bits for trailing synchronization, with bit pattern “10101010”. Therefore the total data rate is 21.3 bits per second (bps). Compared to the method of sending raw data, which would be at least 80 kbps (≈ 8 bits × 10 kHz sampling rate), the proposed method can reduce radio throughput by 3,756 times. As presented in the next section, transmitting power dominates the overall sensor power cost; therefore, the proposed method, while increasing the processing power, can greatly reduce the overall system power.

### IV. Experimental Results

Experiments are performed to evaluate the performance of the custom-designed AFE front-end integrated circuit and to validate the entire wireless aquatic biosensor system. The AFE chip is implemented using Global Foundry 0.18-µm CMOS technology. A micrograph of the chip is shown in Fig. 7 with circuit building blocks highlighted. The chip contains the Low-Noise Pre-Amplifier (LNA), Variable Gain Amplifier (VGA), and Successive Approximation Register Analog-to-Digital Converter (SAR ADC). The overall silicon footprint is 1.5 × 1.5 mm²; the core circuit area is 1 × 1 mm².

The AFE chip, power management circuits, microcontroller (MCU), and the radio transmitter module are placed on a 1.5” × 1” printed circuit board (PCB). A block-level schematic of the PCB is shown in Fig. 8. The schematic includes a right-leg driver (RLD) circuit [26], which consists of an instrumentation amplifier and feedback amplifier. The goal of the RLD circuit is to (a) extract the common-mode signal between inputs $EOD_+$ and $EOD_-$ and (b) drive that common-mode signal towards ground. The RLD electrode is placed in the center of the fish, whereas the $EOD$ electrodes are placed on either side of the tail. An 8 MHz oscillator feeds the MCU and the MCU generates a 100 kHz clock for the SAR ADC. The PCB and battery are encapsulated in a 4” × 2” waterproof plastic case, as illustrated in Fig. 9.
Fig. 7. (a) Micrograph and (b) Layout of the analog front-end IC for EOD signal recording system.

Fig. 8. Block-level schematic of PCB.

A. AFE Performance

The AFE integrated circuit was designed to operate from a single 1.8 V power supply voltage. The simulated and measured frequency response of the LNPA is shown in Fig. 10. The measured closed-loop gain is 37.5 dB. The measured high cut-off frequency is 1.25 kHz while the low cut-off frequency is 14.6 Hz. The total current consumption, including the biasing branch, is 450 nA.

Fig. 11 shows the simulated and measured output-referred noise power spectrum density of the LNPA. In Fig. 11, the measured noise between 1 Hz and 10 Hz is significantly higher than in simulation. While in the closed-loop gain plot (Fig. 10), the slope of the measured gain is slightly steeper between 1 Hz and 10 Hz compared to simulation. These discrepancies are most likely due to inaccurate noise modeling of the pseudo-resistor in the pre-amplifier. Since the pseudo-resistor is operating in the cut-off region in order to create a very large resistance on the order of $10^{10}$ Ohms, it may be very difficult to measure the true resistance and therefore the actual model is difficult to be established [19]. In addition, due to process, voltage, and temperature (PVT) variations, even normal resistors could experience variations in its values between the typical model value and the actual measured values. Additional error may come from the measurement instrument, since the number of sample points is small when measuring low frequencies.

A well-known figure-of-merit used in front-end amplifiers is the Noise Efficiency Factor (NEF) as it assesses the trade-off among a few important parameters such as noise, bandwidth, and total power. NEF is defined as

$$NEF = V_{in,RMS} \sqrt{\frac{2 \cdot I_{TOT}}{\pi \cdot U_T \cdot 4kT \cdot BW}}$$  \hspace{1cm} (1)$$

where $V_{in,RMS}$ is the input-referred noise, $I_{TOT}$ is the total current consumption of the LNPA, $BW$ is the bandwidth of the amplifier and other parameters are as conventionally defined. The measured NEF of the LNPA is 1.8. Table II summarizes the measured results of the proposed LNPA and compares it with similar designs in the literature which focus on amplifying weak bio-potential signals.

The gain of the VGA can be programmed by adjusting the input capacitance of the binary-weighted capacitor array.
been implemented in a free-swimming aquarium environment individually in 56–75 liter aerated aquaria maintained at 25–

been commercially from Segrest Farms (Gibsonton, Florida, USA). Adult fish, 20-35 cm in length, were housed C and were fed three times weekly. The overall system has been implemented in a free-swimming aquarium environment to test its underwater performance. The EOD sensing probe electrodes are placed near the tail of the fish to collect near-field electric field. The probe electrodes are 0.5 mm 316LVM stainless steel. The electrodes are fixed on the fish using flexible elastic bands. A small LiPo battery with 250 mAh capacity provides power for the whole wireless sensor. A 3D-printed backpack is applied to host the circuits and the battery. An annotated picture of the fish carrying the backpack is shown in Fig. 14.

Fig. 15 presents the recorded frequency and amplitude data of the EOD signal collected by the proposed system over a time period of 15 hours. When obtaining the data of Fig. 15, since the sensor was attached close to the target fish, the amplitude of the EOD signal was quite stable, such that it was not necessary to implement automatic gain-feedback. In a more challenging environment, automatic gain-control can be achieved via digital feedback signals from the MCU to select one of 7 gain settings in the VGA. Motion artifact is achieved via digital feedback signals from the MCU to select one of 7 gain settings in the VGA. Motion artifact is minimized to deter excessive movement. Moreover, studies performed to investigate how the EOD of an electric fish is affected by chronic changes in the environment and/or

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<th>Parameter</th>
<th>[19]</th>
<th>[27]</th>
<th>[28]</th>
<th>[29]</th>
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<td>20.3</td>
<td>2.1</td>
<td>1.07</td>
<td>13.7</td>
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<table>
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<tr>
<th>Specification</th>
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<tr>
<td>Technology</td>
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<tr>
<td>Sampling Rate</td>
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</tr>
<tr>
<td>Resolution</td>
<td>8</td>
</tr>
<tr>
<td>ENOB (bit)</td>
<td>7.4</td>
</tr>
<tr>
<td>Power (μW)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Fig. 12. Measured closed-loop gain of the VGA.

Fig. 13. Measured FFT of the ADC at 11.11 kHz sampling rate.

B. EOD Recording Results

In the EOD sensing experiment, the target \textit{S. macrurus} is a freshwater species of knifefish native to South America and was obtained commercially from Segrest Farms (Gibson’s, FL, USA). Adult fish, 20-35 cm in length, were housed individually in 56–75 liter aerated aquaria maintained at 25–28 °C and were fed three times weekly. The overall system has been implemented in a free-swimming aquarium environment...
after surgical or pharmacological manipulations are optimal
when the EOD signal is stable with minimal noise. Hence, to
minimize frequency data that is independent or unrelated to
the fish’s EOD, we implemented the error detection algorithm
that automatically removes data when it is out of range of the
generated fish EOD.

The total power consumption of the wireless EOD signal is
15 mW, of which the TX module consumes 9 mW, the MCU
consumes 6 mW, and the custom-designed AFE integrated

circuit consumes 2.2 µW.

This design provides a prototype of the aquatic biosensor
platform. Individual building blocks, particularly the TX mod-
ule and MCU, have room for optimization. For example, the
super-low power ultra-wideband radio transmitter of [32] can
be used to replace the QAM-TX2 transmitter to reduce the
TX power from 10 µJ/bit to as low as 1 nJ/bit. Moreover, a
custom digital integrated circuit can replace the MCU to save
processing power.

In order to ensure that the receiver is able to detect the
transmitted QAM pulses, in this preliminary experiment, we
allowed the TX module to transmit a digital 1 at full power
without controlling the duty-cycle. On the other hand, using
QAM, a digital 0 is transmitted with 0 power. The sensor
system is able to tolerate full TX power and meet the goal of
15 hours of continuous recording because it only transmits
amplitude and frequency.

V. DISCUSSION AND CONCLUSION

In the reported experiment, the received data are only the
frequency and amplitude; as such, we cannot fully recover the
raw signal. This is arguably the main disadvantage of the
proposed method. However, the most salient information for
the biologist is available. Now, if the user wanted to receive a
port of the raw waveform, a possible solution is to modify
the sensor so that it transmits a portion of raw data when
required, so that other types of analysis can be performed,
such as FFT. Another disadvantage of the proposed system is
the accuracy of the recorded amplitude and frequency, which
is degraded by in-band noise. Adding a measure of in-band
noise to this sensor would allow one to roughly estimate the
accuracy in the measurement.

A novel low power aquatic wireless biosensor has been pre-


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