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# A 0.5 μA/Channel front-end for implantable and external ambulatory ECG recorders

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ABSTRACT

There is an increasing demand for low power, low voltage, and small size analog readout bio-potential systems. This paper presents an analog front-end for measuring the intra-cardiac signals in implantable and also external ambulatory ECG cardiac recording applications. The analog front-end benefits from voltage to frequency conversion without conventional analog to digital conversion and thereby achieves a very low power consumption. The frequency averaging digital reconstruction makes an intrinsic low pass filter of which the cut-off frequency changes with the averaging interval and eliminates the need for an analog filter in this system. Furthermore, this feature enables the development of a general purpose analog readout bio-potential measurement system with programmable bandwidth. The proposed IC is fabricated in a 0.18 μm CMOS process and occupies 0.396 $mm^2$. It can measure intra-cardiac bio-potentials with 9.2-bit resolution while consuming just 0.5 μA per channel from a 1 V supply. The input referred noise of the intra-cardiac signal readout channel is 2 $\mu V_{rms}$.

## 1. Introduction

Cardiovascular diseases are among the leading causes of death. An abnormal rhythm of the heart is an early symptom of a heart disease and perhaps even heart failure, which can get worse if not treated. Monitoring the heart health condition continuously over long periods of time helps specialists to access a meaningful dataset to diagnose and cure this heart disease. Long term recording applications need a small device with a limited resource of power for ease of use. For example, a pacemaker is a disposable medical device that remains inside the body of patient for about 4–8 years before replacement by a new pacemaker with a fresh battery occurs [1]. Also, Implantable Loop Recorders (ILR) or External Event Recorders (EER) use ultra-low energy circuits and systems to record the signals over a long time [15].

A state-of-the-art recorder is required to sense the natural cardiac electric signals (either through peak detection or full waveform acquisition). As the sensing readout channel must continuously monitor the cardiac activity for a long time, the design of the front-end, often called the sense amplifier is very important and hence the design of the sense amplifier must be centered around ultra-low power consumption [2,3,19].

Fig. 1 shows an example of the intrinsic human heart waveform measured by means of external electrodes. The ventricular QRS signal occupies the 20–60 Hz frequency band with an amplitude range of 1–10 mV peak-to-peak. The atrial P signal occupies the 40–100 Hz frequency band with an amplitude range of 0.05–2 mV peak-to-peak. The T signal of ventricular repolarization contains frequencies below 10 Hz. The frequency range of disturbing bio-potential signals coming from muscles is from 100 Hz to 2 kHz and must be filtered out properly [1].

Conventional bio-potential measurement systems use an analog to digital converter to convert the amplified input signal into a digital format. High-gain amplifiers, various filters and high-resolution ADCs are among the usual building blocks of conventional bio-potential systems and consume large area and high power, which both are critical in wearable and implantable devices [4–11,18]. The large amount of data generated by the ADC is then analyzed by a processor, stored and finally the modulated signal is transmitted for further processing. Digital signal processing, storage and transmission are power hungry processes [8].

In this paper, a novel analog front-end is proposed, the output of which is a PWM signal that can be directly processed by a digital processor and/or transmitted without full analog to digital conversion. The proposed system benefits from a voltage-to-frequency conversion technique [13] to produce a PWM signal, the frequency of which is directly related to the input voltage. Making use of a PWM output signal in an ADC-less system leads to reduction of the overall power consumption and area.

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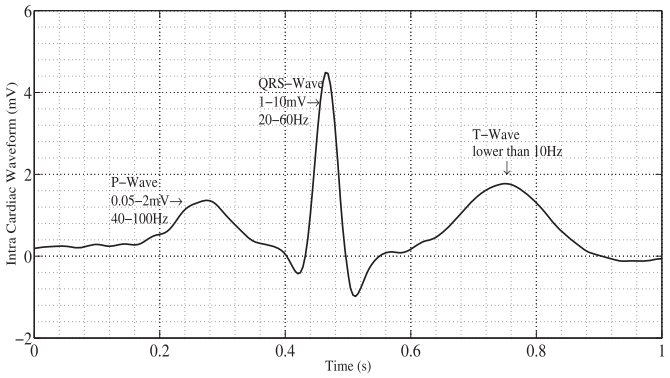


**Fig. 1.** Example of a human electrocardiogram.

This paper is organized as follows: Section 2 describes the architecture of the proposed system that includes voltage to frequency conversion and presents its linearity analysis. Section 3 describes the circuit implementation and its specifications. Section 4 presents the measurement results. Finally, Section 5 concludes the paper.

## 2. Architecture

The proposed bio-potential system uses a voltage to frequency conversion technique that is precise and simple to implement with minimum power consumption.

Fig. 2 shows the proposed system architecture with its constituting building blocks. The proposed system employs 3 instrumentation amplifiers (IA) as input blocks. The main core of the IA is an OTA with a high DC gain. The IA block benefits from capacitive feedback with intrinsic input offset cancelation. The input voltage of the system is a cardiac signal, which is in the range from very low voltages (of about 50 μV) to maxima of about 10 mV. As the dynamic range of the cardiac signal is large, the bio-potential system needs a programmable gain to adapt the dynamic range of the cardiac signal to the dynamic range of the subsequent blocks. The capacitive feedback provides gain programmability with three selectable capacitances. The input referred noise of the IA is the dominant noise source of the whole system, since the first block with a high gain decreases the effect of the subsequent blocks on the input referred noise. The total noise of the IA is mainly due to the noise of the OTA. The negative feedback loop provides noise and signal filtering with a high-pass filter behavior.

The multiplexer selects one of the three IA output signals corresponding to three different leads that could sense three pacemaker, ILR or EER electrodes pairs. The sample-and-hold block holds the samples of the selected IA in each period for sensing. The differential output of the sample-and-hold is transformed into a current by means of a transconductance amplifier with a 1 μS gain. The output current of the transconductor feeds the charge pump in the current-controlled oscillator (CCO) which produces a saw-tooth waveform by charging and discharging a capacitance via two controlling switches. These switches play a key role in controlling the time of charge and discharge. The value of the capacitance and the transconductor current determine the rate of this operation.

The next important block is a Schmitt trigger, which is responsible for comparing the saw-tooth waveform with the Schmitt trigger's high and low reference levels and changing its state accordingly. The Schmitt trigger is the most important block that affects the linearity of the whole system. The output of the Schmitt trigger provides the switching signals for the charge pump as well as the output of the bio-potential system. This output voltage is a pulse modulated signal that represents the bio-potential signal. A higher output pulse frequency means a higher cardiac input voltage that causes higher charging and discharging rate.

Fig. 3 shows an example of the generated signals and the concept of the used voltage to frequency conversion. The output current of the transconductor increases when the input voltage goes high. The higher output current of the transconductance increases the rate of charging and discharging. Consequently, the Schmitt trigger produces a higher PWM frequency from the saw-tooth voltage across the capacitance. Through counting the zero crossings of the pulses in a specific time interval, the input voltage of the cardiac signal can be reconstructed from the output PWM voltage as will be explained next.

### 2.1. Voltage to frequency transfer function

The output period, $T$, is the duration of subsequent charging ($T_{ch}$) and discharging ($T_{disch}$) within the Schmitt trigger decision levels. It holds:

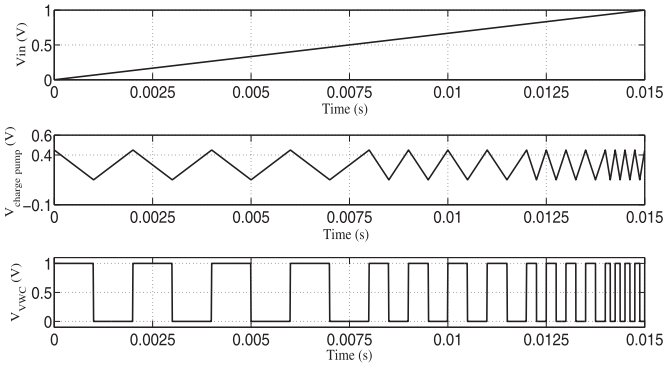


**Fig. 3.** Voltage-to-frequency concept. Using a ramp waveform as input voltage, the CCO capacitor voltage changes at a higher rate with higher input voltage. The output signal has a FSK-PWM waveform.

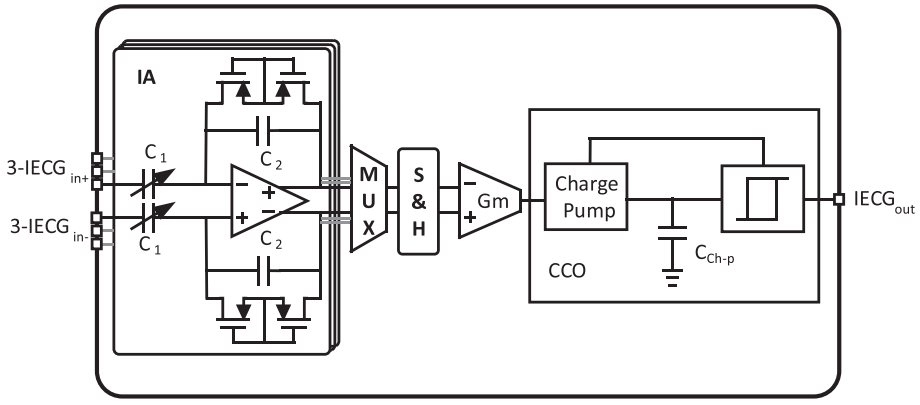


**Fig. 2.** Bio-potential measurement system architecture.