

# A Two-Electrode 2.88nJ/Conversion Biopotential Acquisition System for Portable Healthcare Device

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## Abstract

A 2.88nJ/Conversion low energy biopotential acquisition system is designed for portable healthcare device. Two dry copper contact electrodes with 1.2-cm diameter are used to easily interface between skin and healthcare device. Chopping technique is adopted at readout front end to obtain thermal noise floor of 1.3uVrms over 0.5~200Hz and CMRR over 100dB to mitigate common-mode body potential induced from AC power line. A 4-stage gain control and band selection blocks are integrated to digitally calibrate for different types of biomedical signal and an 8-bit synchronous successive approximation register (SAR) A/D is used to digitize sensed biopotentials. A test chip is implemented in 0.18um, 1.8V supply CMOS technology and successively verified by readout ECG signal with two electrodes contact at chest of body with separating 6cm.

## I. INTRODUCTION

ECG, EMG and EEG are common biomedical signals that give continuous information for patients undergoing surgery or those admitted to intensive care units (ICUs). Conventionally, patients are measured by bulky and main-powered instrument with several wired leads connected on body which can greatly reduce patient's mobility and white coat effect in hospital also makes an erroneous diagnosis. Common portable health care approaches which use three Ag/AgCl electrodes with conductive solution provide good signal quality in Skin-Electrode interface [1]. However, it has the problem of inconvenient patient attachment; also it may cause inflammation of the human skin and limits its reusability and continuous health monitoring. Furthermore, the third reference electrode forms a low impedance node to ground. Hence, patients suffer from hazard of leakage current. Consequently, a low energy, small form factor, two dry electrodes biopotential acquisition system is attractive for ambulatory healthcare application. Previously, several types of commercial metals were investigated as a wearable electrode [2]. The impedance fluctuation of the different metal electrodes is less than one decade in the frequency range less than 1kHz compared with Ag/AgCl. This indicates that a

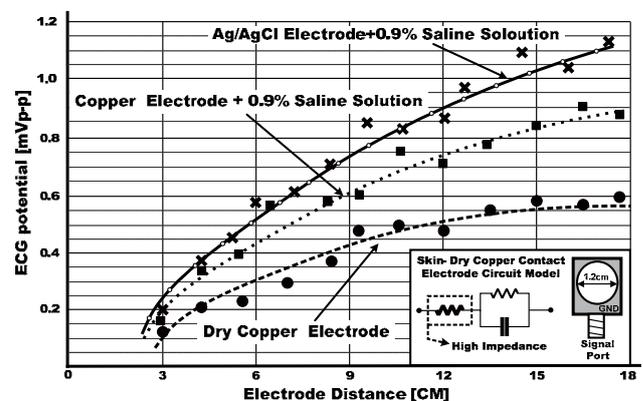


Fig. 1 Electrode comparison between conventional Ag/AgCl with saline solution and dry PCB type copper contact electrode

copper on PCB as an interface between skin and portable instrument can replace the Ag/AgCl electrode without any electrically conductive solution. However, its main drawback is that power line interference problem is severe in two-electrode recording system [3][4]. Short distance between two electrodes can reduce electromagnetic interference (EMI) in biopotential measurements since this approach will cause power line 60Hz noise common to readout front end. However, it also suppresses differential signal strength because of the short distance between the electrodes. Moreover, due to the lack of the conductive solution, the skin-electrode interface impedance of dry electrode is much larger than conventional Ag/AgCl electrode which could also degrade signal potential as shown in Fig.1. Therefore, in order to extract biopotentials under such circumstances, the noise and CMRR requirements of analog readout front end are more stringent, while consuming low power. According to [4], only a micro volts noise level is allowed to maintain recorded signal quality at the front end and over 100dB in band CMRR and PSRR of readout front end are also required for robust operation regards to power line interference in such circumstances. Simultaneously, the biopotential acquisition system need to have a programmability for its gain and bandwidth [5] to meet different signal potential and frequency characteristics.

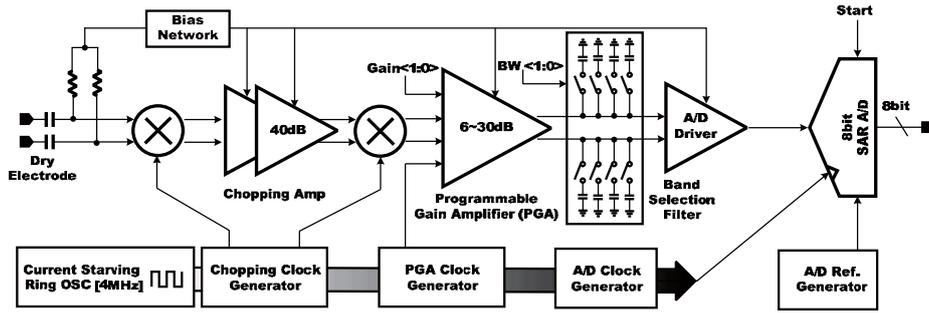


Fig. 2 The Proposed Architecture of Low Noise, Low Energy, Two-Electrode Biomedical Signal Acquisition System

In this paper, the proposed architecture of a low noise, low energy, two dry electrodes biopotential acquisition system is described in Section II. In Section III, The building blocks including low noise, micro power chopping amplifier, programmable gain and band selection stage, low energy 8-bit Synchronous SAR A/D are discussed. In Section IV, Measurement results are presented. Finally, the conclusion is given.

## II. THE PROPOSED ARCHITECTURE OF TWO-ELECTRODE BIOPOTENTIAL ACQUISITION SYSTEM

Fig.2 shows the Architecture of the proposed low noise, low energy, two-electrode biopotential acquisition system. It mainly consists of Bio-Amp and A/D. The sensed biomedical signal through copper contact electrode firstly DC coupled and low noise pre-amplified by Bio-Amp while consuming minimum power. Low energy consumption could be achieved through the 8-bit SAR A/D which can continuously digitize the sensed biopotential in high sampling rate. Bio-Amp includes low noise chopping amplifier (Amp.) cascaded by switched capacitor (SC) type digitally programmable gain and bandwidth selection stage.  $KT/C$  noise can be minimally referred to input stage by allocating 40dB in-band gain to chopping stage. Finally, a 1x A/D driver is operated as a differential to single-ended converter to interface between Bio-Amp and A/D. SAR A/D is designed by 8-bit binary weighted capacitor type D/A with unit capacitor of 30fF and a low power dynamic comparator with 8-bit unified sequencer and code register type SAR logic. An On-chip 4MHz current starving ring oscillator with variable frequency divider is integrated to provide different types of frequency including chopping frequency of 7.8kHz, a frequency of 125kHz as a PGA clock to switch capacitor and a programmable ADC sampling clock for operating SAR A/D. The bias network generates various bias voltages for Bio-Amp block and a design [6] based on resistively weighted difference between the gate-source voltages of NMOS and PMOS as the A/D reference.

## III. BUILDING BLOCKS OF THE BIO-AMP

### A. Chopping Amplifier

In two electrodes recording system, the principle interference contribution is due to the displacement current from AC power line induced into the patient body. This leads to the total input-referred interference voltage as

$$V_i = V_{id} + V_{ic} \left( \frac{1}{CMRR} + \left\{ \frac{Z_{CM}}{Z_{CM} + Z_i} - \frac{Z_{CM}}{Z_{CM} + Z_i + \Delta Z_i} \right\} \right) + V_{in} \quad (1)$$

Where total input-referred interference voltage  $V_i$  can be expressed in terms of common mode and differential mode voltage at readout front end's input  $V_{ic}$  and  $V_{id}$  which produced by the displacement current.  $Z_{CM}$  represents input common-mode impedance of amplifier and  $Z_i, \Delta Z_i$  represent skin-electrode interface impedance and it's mismatch.  $V_{in}$  is input-referred offset voltage generated by the front end circuit. Thanks to PCB fabrication technology, we can minimize  $\Delta Z_i$  to reduce loading effect of high impedance electrode. Analog chopping technique [7] is adopted to dynamically improve CMRR and PSRR and minimize low frequency noise caused by front end circuit. Fig.3 shows proposed low noise, low power chopping Amp topology. The input chopper modulates input signal to chopping frequency and after two-

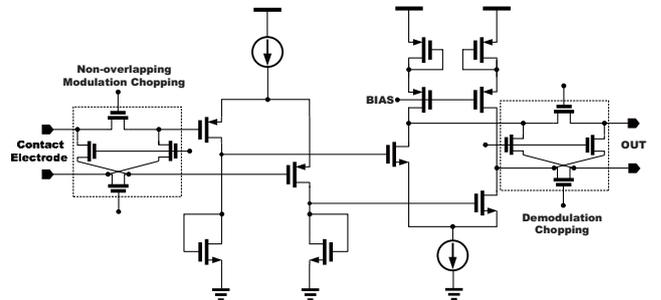


Fig. 3 Low Power Chopping Amplifier

stage amplification then demodulated, while offset voltage is modulated to chopping frequency and then low pass filtered by simple Gm-C filter. Two-stage amplification extends the bandwidth of chopping amplifier to reduce residual offset when demodulated. This stage provides 40dB DC gain and its thermal noise floor of 40nV/sqrtHz while consuming only 2uA from 1.8V supply voltage. The noise efficiency factor introduced in (2)[8] shows 5.1 over 200Hz bandwidth.

$$NEF = V_{ni,rms} \sqrt{\frac{2I_{total}}{\pi V_i 4kT.BW}} \quad (2)$$

**B. Programmable Gain and Band Selection Circuits**

Fig.4 shows Pseudo-Differential programmable gain and band selection circuits. The Programmable Gain Stage organizes binary weighted capacitor to configure the Bio-Amp gain. This design provides a variable DC gain from 6dB~30dB and 10pF internal miller capacitor is nested to suppress switching glitches to improve signal quality. Band selection filter is designed by switching load capacitor to set cutoff frequency of 300Hz, 1kHz, 10kHz. Finally a 1x buffer stage is added to drive A/D.

**C. Low Energy Fully Synchronous SAR A/D**

Low Energy 8-bit SAR A/D with unified sequencer and code register SAR logic is shown in Fig.5.and Fig.6. Both Delta-Sigma and successive approximation A/D are well suited to meet the low power consumption and optimized for operation at low speed required biomedical application. However, SAR A/D which is shown in Fig.5 superior to Delta-Sigma architecture in simple hardware required and minimal analog blocks to achieve low energy consumption at the same sampling rate. Most common design of the SAR logic is separated sequencer code register architecture [9]. Despite of its simplicity and easy layout which consist of identical 16 F/F to provide 8-bit SAR, it's successive approximation algorithm is realized by sequencer synchronously control the code register. Then the code register operates asynchronously control the digital inputs to binary capacitor array since the clock input to a particular F/F is obtained from the output of the succeeding F/F. Fig.6 shows unified sequencer and code register SAR logic. In this design a single Set/Reset F/F is used in each bit cell which can functions both sequencer and code register. Consequently, Only 8 F/F was required and it operates synchronously to

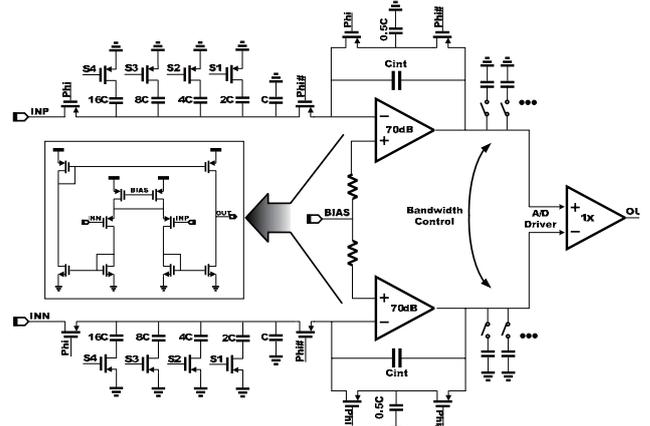


Fig. 4 Pseudo-Differential Switched Capacitor Type Programmable Gain and Band Selection Circuits

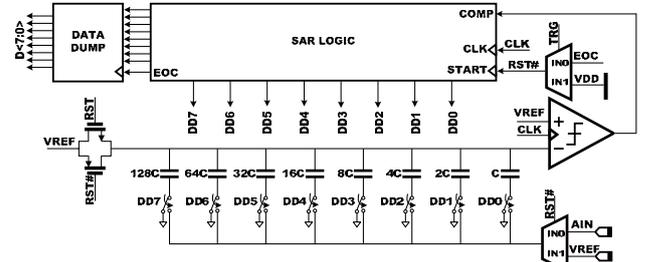


Fig. 5 8-bit low energy fully synchronous SAR A/D

complete successive approximation algorithm. Two standard F/F is added to generate End of Conversion (EOC) signal to parallelize the 8-bit output code.

**IV. PROPOSED SYSTEM MEASUREMENT RESULTS**

The proposed biopotential acquisition system was tested by using simple two PCB copper pads as the electrodes with the distance of 6cm to sensing ECG signal. Fig.7 shows Amplified ECG waveform by two-electrode Bio-Amp with the gain of 60dB and bandwidth of 300Hz. A TI 3-electrode simplified ECG circuit introduced in [10] is also integrated on the same test board to compare the sensed signal quality. It shows that proposed two-electrode Bio-Amp clearly track the PQRST information of ECG signal.

Fig.8 shows FFT results of 8-bit SAR A/D. The measured SNDR of 47.5dB with the sine input frequency of 1kHz and 400mVp-p while consuming only 4.2uW. Table I summarizes the performance of the proposed system. The proposed system was fabricated in 0.18um CMOS process and its die area of

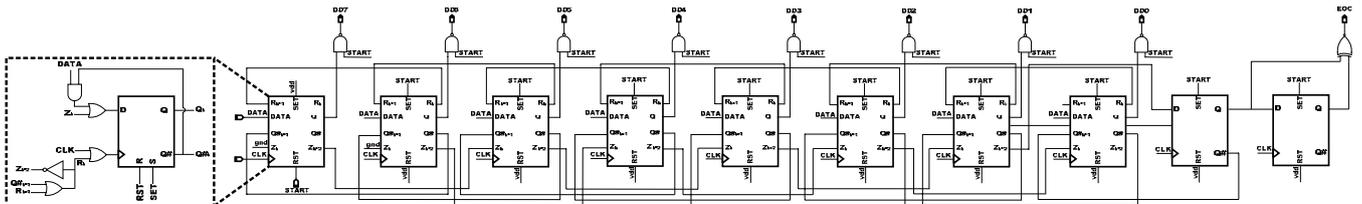


Fig. 6 Unified Sequencer and Code Register 8-bit SAR Logic

1.2mm x 2mm as shown in Fig.9.

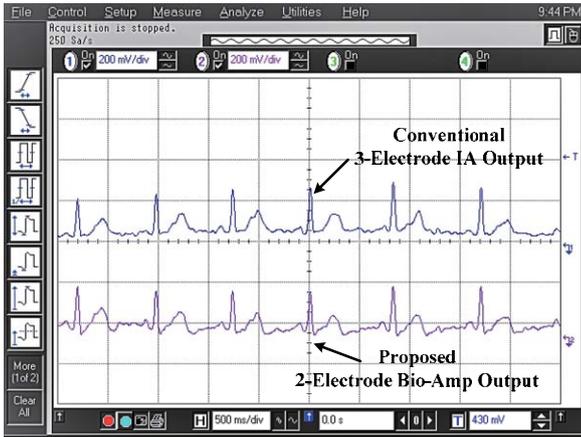


Fig.7. Measured ECG Signal at human chest

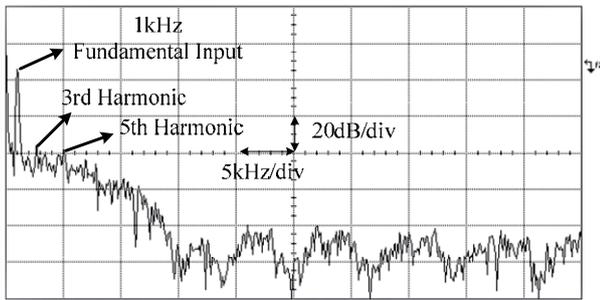


Fig.8. FFT Results of SAR A/D with 1kHz input

## V. CONCLUSIONS

We propose a Two-Electrode 2.88nJ/conversion biopotential acquisition system which is suited for energy constrained portable healthcare device. Two copper contact pads are used for signal acquisition to achieve mobile health monitoring. Chopping technique was adopted to compensate copper electrodes imperfection and reduce power line interference. The total power consumption of the system is 40uW with the operation of 125 kHz to yield 2.88nJ/Sample. The chip was verified by successively recording ECG signal with separating two copper contact pads of 6cm.

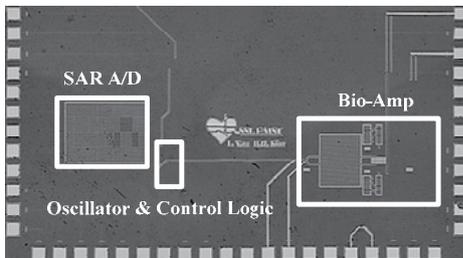


Fig. 9 Chip micro-photograph

TABLE 1  
Performance Summary of Biopotential Acquisition System

Bio-Amp Performance	Supply Voltage[V]	1.8
	Electronic Gain Selection[dB]	46 ~ 70
	Electronic Band Selection[kHz]	0.3~10.0
	Input Referred Noise Voltage [Vrms]	1.3uVrms (@0.5~200Hz)
	Total Harmonic Distortion(THD)	<1%(@ minimum Gain)
	CMRR & PSRR(@60Hz)	>100dB
Power Consumption	36uW	
SAR A/D	Input Range	0.0~0.8V
	Sampling Rate	31.5kHz~500kHz
	Unit Capacitance	30fF
	ENOB	7.6 (@1KHz Sine Input)
	Power Consumption	4.2uW (@125KHz)
	DNL /INL	<±0.6LSB Typical
	Energy Per Sample	2.88nJ/Conversion

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