Very Low Power Sigma Delta Modulator for Biomedical Applications

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Abstract: *This paper discusses the design of picowatt power Sigma-delta modulator with genetic algorithm (GA) based oversampling technology. This Sigma-delta modulator design is paid special attention to its low power application of portable electronic system in digitizing biomedical signals such as Electro-cardiogram (ECG), Electroencephalogram (EEG) etc. [1]. A high performance, low power second order Sigma-delta modulator is more useful in analog signal acquisition system. Using Sigma-delta modulator can reduce the power consumption and cost in the whole system. The original biomedical signal can be reconstructed by simply applying the digital bit stream from the modulator output through a low-pass filter. The loop filter of this modulator has been implemented by using switch capacitor (SC) integrators and using simple circuitry consists of OpAmps, Comparator and DAC. In general, the resolution of modulator is about 12-16 bits for biomedical application. In this second order Sigma-delta modulator simulation results of shows a 68 dB signal-to-noise-and distortion ratio (SNDR) in 200 Hz biomedical signal bandwidth and a sampling frequency equal to 1MHz in the 0.18 μ CMOS technology. The power consumption is 1.45 pw. It is very suitable for low power application of biomedical instrument design.*
Keywords: Sigma Delta Modulator(SDM), Biomedical System, Genetic Algorithm, ECG, EEG etc.

I. Introduction

The application of portable electronic systems such as wireless communication devices, consumer electronics and battery powered biomedical devices increases the requirement for low-voltage and low power circuit techniques [2]. Designing of low-voltage circuit can reduce the number of battery cells for low weight and small system size. At the same time, low power circuit design can increase the operation time for biomedical application [3]. Sigma-delta modulator has become a usual technique for analog-to-digital (A/D) conversion. This is because sigma-delta modulator circuits are structured simply with low-accuracy analog parts and very suitable in low frequency, high performance and low power application. The single-bit signals of sigma delta modulator are converted into multi-bit signals at the Nyquist sampling rate for biomedical application. Thus, currently usable types of biomedical systems with sigma-delta based A/D converter need single-bit conversion hardware including decimation filter. The signal extracted out of biological source is called as Biomedical Signal. Sigma-delta modulator utilizes a negative feedback loop consist of an integrator, comparator and one-bit DAC that are very simple components. The input analog signal is first integrated and compared with ground using comparator. Its output drives a one bit DAC which switches reference voltages to the summing node of the integrator, minimizing the difference signal. In this paper, the second order sigma delta modulator can be widely utilized for low-power with biomedical applications. Further power savings can be achieved by using relatively low oversampling ratios. The Biomedical signal acquisition system must extract and amplify the low level signal (0-20mV). The table 1.1 shows the various biomedical signals ranging from 10 to 200 Hz. High resolution of sigma delta converters allows the small signals to be acquired directly, without the use of instrumentation amplifiers. The large common mode signals can be digitized without saturation and the small differential signals can be recovered with resolutions comparable to conventional methods. Genetic algorithm (GA) have been successfully applied to a wide range of optimization problems including design, scheduling, routing, and signal processing.

In sigma-delta (ΣΔ) modulator design, GA can be effectively used to optimize the scaling coefficients in order to achieve the desired signal-to-noise ratio [9][10]. ΣΔ modulators were traditionally used for audio applications where the over-sampling ratio is high and a high resolution can be achieved with a realizable clock frequency.

II.   Principle And Analog Circuit Design

First of all, we must choose between a switched capacitor (discrete-time) and a conventional active RC (continuous-time) [4] for integrator in designing any sigma delta modulator. Generally, most integrated circuit implementation of sigma delta ADCs use SC circuits because it are easily simulated, compatible with VLSI CMOS process and insensitive to clock jitter [5]. Second order sigma delta modulator consists of two integrator, 1-bit ADC, and 1-bit DAC. The power of the first integrator is the major consumption to the overall power dissipation in sigma delta modulator. For that reason, a substantial amount of power can be greatly saved by a suitable circuit design. The finite DC-gain, noise and distortion of the operation amplifier will be determined on

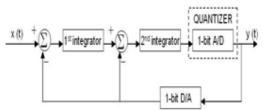| Sr. No	Biomedical Signals	Frequency Range (Hz)
1.	Electroretinogram (A graphic recording of retina characteristics.)	0-10
2.	Electronystagmogram (A graphic recording of involuntary movements of the eyes.)	0-20
3.	Pneumatogram (A graphic recording of respiratory activity.)	0-40
4.	Electrocardiogram(ECG)	0-100
5.	Electroencephalogram (EEG)	0-100
6.	Electromyogram (A graphic recording of muscular action such as muscular contraction.)	10-200
7.	Sphygmomanogram (A recording of blood pressure.)	0-200

Table 1.1: Biomedical Signals

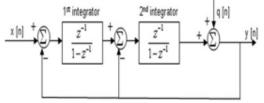**Fig 1.** Block diagram of second-order Sigma Delta Modulator.

Fig 2. Simplified model for second order Sigma Delta Modulator.

the first integrator that will reduce the performance of the whole sigma delta modulator, since these errors will be added directly to the input signal. Furthermore, fully differential structure is used to design integrator and shown in Figure 3. The advantages for this design can improve the noise in the sampling time to increase the resolution of device, reduce the even harmonic and increase the input range. At the same time, the correlated double sampling (CDS) is addition to this integrator that can suppress flicker noise, thermal noise and offset voltage. The schematic of a CDS integrator is shown in Figure 3 [5]. It is clear that the SNR can be increased by increasing the oversampling ratio in any order modulator. If oversampling ratio increases, the modulator will be operated in higher speed and consumed more power. So, further power saving can be achieved by using relatively low oversampling ratios (OSR=fs/2fin)

2.1 Operation Amplifier (OpAmp) and Common Mode Feedback (CMFB)

The integrators include operation amplifier (OpAmp) that is the most critical element and mainly

influence the whole performance of modulator. In general, the operation amplifier (OpAmp) in the integrator determines on the operation speed and performance of the modulator. It consumes the power proportional to the gain. Approximately 60dB of dc gain is required to prevent performance degradation and maintain a 12-bit dynamic range [5]. The specifications of OpAmp shown in Table I In order to combine the high gain and low power requirement, a fully differential folded-cascode operation amplifier has been used and shown in Figure 4. The gain bandwidth (GBW) and the open-loop gain (Av) of the amplifier are given by

$$GBW \approx \frac{g_{m1}}{C_L}$$

$$A_v \approx g_{m1}(g_{m6}r_{o6}r_{o4} // g_{m8}r_{o8}(r_{o2} // r_{o10})$$

At the same time, the Common Mode Feedback (CMFB) of an amplifier is a critical in discrete time (DT) for low voltage and low power application, because it will not reduce the output swing and also require little power only. The common mode output level of the amplifier is maintained by the feedback circuitry also shown in Figure 3 given below.

This CMFB circuit has a drawback that common mode level depends on the parameter of device, but the advantage of this circuit is current-path-reduction. In the low power design, this is a very important consideration. Anyway, in a well-design circuit, the loop gain must be relatively high. The closed-loop gain is approximately equal to 1/β , where β represents the feedback factor and the open-loop gain of the common mode feedback are given by
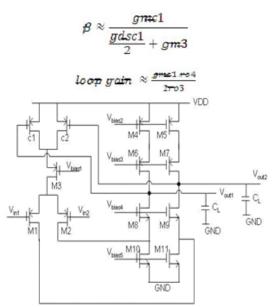
$$\beta \approx \frac{gmc1}{\frac{gdsc1}{2} + gm3}$$

$$loop\ gain \approx \frac{gmc1\ ro4}{2ro3}$$

Fig 3. Fully differential folded-cascode operation amplifier.

2.2 Comparator

The purpose of the comparator in a sigma delta modulator is to quantize a signal in the loop and provide the digital output of the modulator. The performance of the sigma delta modulator is relatively insensitive to offset and hysteresis in the comparator as the two level quantizer, because the effects of these impairments are attenuated in the baseband by second order noise shaping that can be filtered by decimation filter. The regenerative latch shown in Figure 5 has been used to implement in the comparator because periodic answers are required in all loops of sigma delta and the bit-stream signal can be utilized in the communication application [6]. Thus, power and chip area can be saved.

2.3 1-bit DAC

The purpose of a feedback DAC in a closed-loop sigma delta modulator is to convert the modulator s digital output back into an analog form to be compared to its analog input. In essence, the DAC controls the mapping between the analog and digital domains. Therefore, the performance of the closed-loop sigma delta modulator is

completely dependent on the accuracy of its feedback DAC and the way in which its output is compared to the modulator input [5] One of the features in the sigma delta modulators is that they can use low-
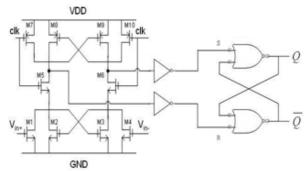

Fig 4. Comparator implemented with the latch.

resolution of DACs in their feedback paths but that is not the same meaning as low accuracy. Actuality, if a multibit DAC is used, the linearity of the DAC must match completely the overall linearity requirements of the modulator. For that reason, 1-bit DACs are typically used in sigma delta modulator. Since they only have two levels, all step sizes are identical. There are, however, other mechanisms that can be separated into two categories for nonidealities in the 1-bit DAC are nonidealities associated with the voltage reference and with the way the charge is taken from the reference [7].
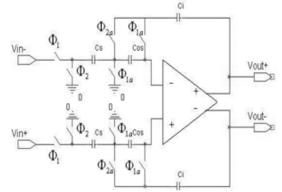

Fig 5. The circuit schematic of integrator with CDS in the Sigma-Delta Modulator.

III. GA-Based Coefficient Optimization
3.1 Genetic Algorithm

GAs are search and optimization algorithms based on the mechanics of natural selection and natural enetics [8]. They make use of structured but randomized information exchange and concept of the survival of the fittest. The algorithm starts with an initial population which consists of a collection of chromosomes i.e. possible solutions coded in the form of strings. The chromosome which produces the minimum error function value represents the best solution.
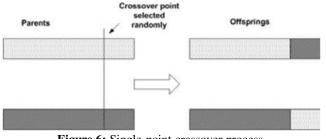

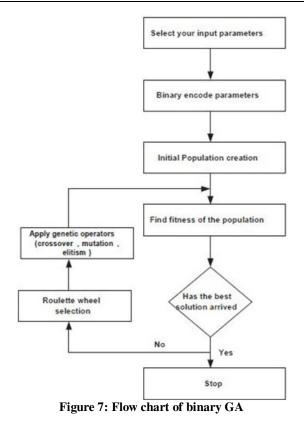**Figure 6:** Single-point crossover process

The chromosomes which represent the better solutions are selected using roulette wheel selection

technique. Genetic operators like crossover, mutation, elitism etc. are applied over the selected chromosomes. As a result a new set of chromosome is produced. This process is repeated until a fit solution appears. In essence, a population of chromosomes is always available to get the desired result. Occasionally a new part is added to a chromosome to make it more robust. Genetic algorithms exploit past to extrapolate new search points to provide improved performance. A robust method like GA works well across a wide range of problems and also is more efficient. The traditional derivatives based approach, enumerative schemes and simple random walks are not that good for all classes of problems. On the other hand, heuristics approaches, such as genetic algorithms (GAs), differ from the traditional ones in that there exists a high probability that the global optimal solution will be reached. Fig.6 shows the flowchart of the binary GA.

3.2 Using GA in ΣΔ ADC Design
In the design of ΣΔ ADCs, we need to optimize a large set of parameters including the overall structures and the performance of the building blocks to achieve the required signal-to-noise ratio. Therefore, behavioral simulations were carried out using a set of Simulink models in MATLAB Simulink environment in order to verify the performance for a Biomedical system, to investigate the circuit non-idealities effect, to optimize the system parameters and to establish the specifications for the analog cells. The most important parameter to be optimized in a sigma-delta modulator are the gain coefficients in order to achieve the desired signal-to-noise ratio. GA is one of the best optimization technique which finds a global optimum solution without taking much of the computational power. The steps involved in the process of optimization using GA is shown in Fig. 3. There are two general schemes for coding the solutions: (i) binary coding (ii) decimal coding. In our work, binary coding has been used where 0s and 1s are used to form a chromosome of length l depending on the precision needed. After defining the chromosome, an initial population is obtained by randomly producing N number of chromosomal solutions called the first generation. The next step, called pairing, consists of selecting the chromosomes that will pair together to reproduce the offsprings. This is done by using the chromosome, an initial population is obtained by randomly producing N number of chromosomal solutions called the first generation. The next step, called pairing, consists of selecting the chromosomes that will pair together to reproduce the offsprings. This is done by using roulette wheel selection technique. These pairs will be used for reproduction. Reproduction ensures that chromosomes with higher fitness will have a higher probability of reproduction than chromosomes with lower fitness. Reproduction is the application of crossover, mutation and elitism operators over the selected chromosomes. In this work single point crossover has been used as shown in Fig. 6. Mutation rate (MR) is set to a very low value. A high MR introduces high diversity but might cause instability. However, a very low MR makes it difficult for the GA to find a global optimal solution. In addition to crossover and mutation the best chromosome present in a particular generation is passed on to the next generation so that it will not be lost until the next best arrives. In this way the stability of the GA is improved. A fitness function or objective function has to be obtained to evaluate the performance of the chromosomes and compare their performance. In the design of sigma-delta modulator we need to optimize the coefficients for a maximum signal-to-noise ratio (SNR).
Hence the fitness function is formulated as After evaluating the fitness function, fitness values will be assigned to each chromosome. If the best fit chromosome has arrived, the GA can be stopped and the coefficient values can be decoded. Otherwise the chromosomes are sent back to the selection module and the whole procedure is repeated again until the best arrives or the maximum number of generation set is reached. It is to be noted that the number of chromosomes should not be very small or very high. Too small a population size will lead to very fast convergence of GA and thus one may not obtain an optimum solution. Too high a population size will take a lot of computation time for the GA to converge which needs sufficient computing power.

Figure 7: Flow chart of binary GA

$$fitness = (1/Error)$$

where

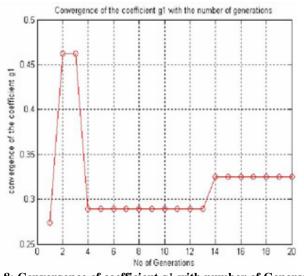$$Error = DesiredSNR - ObtainedSNR$$

Figure 8: Convergence of coefficient g1 with number of Generations

3.3 Simulation Results:

Parameters	Switch capacitor SDM	SDM using Genetic Algorithm
Signal Bandwidth	150 Hz	150 Hz
Sampling Frequency	51 KHz	51 KHz
Oversampling Ratio (OSR)	128	128
Gain Coefficients	g 1=g2 =0.5	g 1=0.27 , g2 =0.5
Signal to Noise Ratio	70.2 dB	89.1 dB
Effective no. of bits (ENOB)	11.36 bits	14.50 bits
Avg. Power Consumption	1.90 pW	1.45 pW
Power Supply Voltage	1V	1V
Technology	0.18 µm	0.18 µm

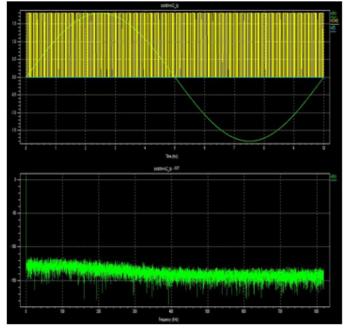**Table 1.2:** Table showing Simulation Results of SDM

Fig.9: Output and power spectrum of SDM

IV.   Conclusion

Designing low-power of two order discrete-time sigma delta modulator has been presented. Due to the lower bandwidth of biomedical signals, sigma delta modulation is feasible. A low power sigma delta can be designed by simple circuit that either modulating or recovering circuit with oversampling technique. Using oversampling technique, not only the restraints in analogy circuit can be relaxed, the quantization noise can also be reduced. After all, the analog biomedical signal can be reconstructed from the digital bit stream of modulator output by simple low pass filter.

A GA-based search engine is developed for the quick and easy design of sigma-delta modulators. The genetic algorithm based search engine can effectively search for solutions with different characteristics and enables tradeoffs between different design considerations like power and topology. It has been successfully used

to lower the power consumption in picowatt for a second order sigma-delta ADC which is proposed for Biomedical applications. The coefficients can be optimized using GA which results in extended dynamic range. It has also been applied to a traditional second order feedback topology to find peak SNR values with good stability.

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