# A Comparative Analysis of CMOS Amplifiers for ECG Signals

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**Abstract -** *Over the last few years, there has been a tremendous exploration in VLSI industries in response to scaling trends towards deep submicron technology. Demand for low power and efficient amplification are rising in day-to-day life. The rapid scaling of CMOS processes in nanometer demand low supply, which helped digital circuit realization at very low power consumption. But it is not true for analog circuit realization. The associated drawback is short channel effect which results in low gain stages, decreased impedance etc. Different amplifiers are used to overcome these drawbacks but out of all those amplifiers, Operational Transconductance Amplifier (OTA) gives substantial results in the analysis of performance parameters. This project discusses about the performance analysis of amplifiers like Op-Amp, differential amplifier, instrumental amplifier, isolation amplifier, OTA for the amplification of ECG signals using CMOS technologies. The Operational Transconductance amplifier (OTA) plays an important role in Biological signal measuring electronic equipment like Electroencephalography (EEG) and Electrocardiography (ECG) systems which measure the health and activities of brain, heart, etc. The amplifiers are compared based on different performance parameters. The operational transconductance amplifier (OTA) is an amplifier whose differential input voltage produces an output current. Thus, it is a voltage controlled current source (VCCS). There is usually an additional input for a current to control the amplifier's transconductance. The OTA is similar to a standard operational amplifier in that it has a high impedance differential input stage and that it may be used with negative feedback. Various methods have been employed to increase the performance of the amplifiers for biomedical applications. Thus, further research would lead to a high performance Operational Transconductance Amplifier (OTA) implemented in CMOS technology with increased gain and CMRR along with low power consumption.*

*Keywords: Voltage Controlled Current Source (VCCS), operational transconductance amplifier (OTA), Electroencephalography (EEG), Electrocardiography (ECG).*

## 1. INTRODUCTION

The designing of high performance analog integrated circuits is becoming most essential with the continuous trend towards the reduced supply voltages and transistor channel length. Due to recent development in VLSI technology the size of transistors decreases and power supply also decreases. MOS is most successful among all because it can be scaled down to smaller dimensions for higher performance. The size can be reduced to micrometer or nanometer for getting higher performance. On scaling down the Transistor size the most important advantage is one can integrate more number of transistors on the same size and one can get a faster amplifier compared to previous one. This leads to continuous growth of the processing capacity per chip and operating frequency.

Operational amplifiers are the most popular building blocks for analog circuit design. However, op-amp has limitations in bandwidth and slew rate which lead the analog designer to search for other possibilities. Recently operational transconductance amplifier (OTA) has been found to be one of the most significant building blocks in analog signal processing. In high-frequency continuous-time filters, OTA-C filters have often been employed since OTAs provide high bandwidth, high slew rate, and a transconductance gain which can be electronically controlled using a bias current. Hence the circuits developed using OTAs are most likely to possess intrinsic electronic control of parameters such as the cutoff frequency, quality factor, gain of a filter or frequency of oscillation, and the condition of oscillation of an oscillator. Designing high performance analog integrated circuits in low power applications with reduced channel length devices is becoming increasingly exigent with the relentless trend towards reduced supply voltages. A large part of the success of the MOS transistor is due to the fact that it can be scaled to increasingly smaller dimensions, which results in higher performance. On the other hand for different aspect ratio, there is a trade-off among speed, power, gain and other performance parameters. Thus realization of a CMOS OTA that combines a high linearity, considerable dc gain with high unity gain frequency would be a constraint in circuits and systems design task. The instrumentation amplifier is essential element at the read out circuit of any system that deals with low level signals like ECG signals. Differing from a general purpose instrumentation amplifier, must be capable of rejecting common mode signals. OTA using a current division technique is employed to small transconductance, is the basic building block of instrumentation amplifier.

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## 2. LITERATURE SURVEY

This topic discusses about presenting the methodologies used in past and the improvements using at present for overcoming the previous faults of various amplification techniques by having a literature survey and clear explanation on the idea of implementing the project came from the existing methodologies and also general outline for the solution.

Bio-medical signal measurement systems like ECG, EEG, and MRI are having an input voltage ranging from 1-5 mV. Since these signals from human body are very low voltage signals, they must be amplified so that those amplified are most useful for the doctors to analyse the patients' condition and by then to proceed according to the result for further diagnosing.

In earlier days differential and normal op-amps are used in ECG systems to amplify the ECG signals. But they are not much efficient in amplification resulting improper diagnosis of disease especially in heart patients. So, there is a need of an efficient amplifier for perfect diagnosing. After many researches, OTA is claimed as the most prominent amplifier for this problem since; it follows transconductance technique offering more output current for small differential input voltage.

In this paper, comparative analysis of amplifiers for better amplification of ECG signals is done. Among those amplifiers, this IA can be used in low power, low voltage. High CMRR applications are necessary for biomedical instruments. It is given by the CMOS Instrumentation amplifier using OTA. The common mode rejection ratio was found to be 124dB. Therefore, finally the application of read-out circuit has high viability to be using in biomedical applications.

## 3. PROPOSED METHODOLOGY

In olden days, the amplification section in the ECG system is made up of either differential amplifier or operational amplifier.The ECG system shown below on Figure 1 is having an instrumental amplifier made up of OTA which gives better amplification than the former amplifiers. The ECG system comprises four stages, each stage is as following:

(1) The first stage is a transducer- AgCl electrode, which convert ECG into electrical voltage. The voltage is in the range of 1 mV ~ 5 mV.

(2) The second stage is an instrumentation amplifier (Analog Device, AD624), which has a very high CMRR (90dB) and high gain (1000), with power supply +9V and -9V.

(3) The third stage is an opto-coupler (NEC PS2506) to isolate the In-Amp and output.

(4) After the opto-coupler is a band pass filter of 0.04 Hz to 150 Hz filter. It's implemented by cascading a low-pass filter and a high pass filter.
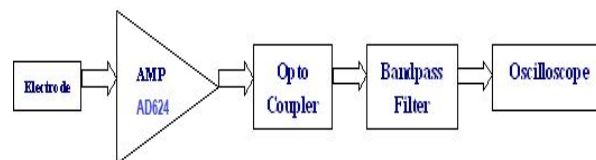


**Figure 1** Block Diagram of ECG recording system

The ECG signal is converted into electrical voltage by electrodes. A typical surface electrode used for ECG recording is made of Ag/AgCl. The disposable electrodes are attached to the patient's skin and can be easily removed. Once the electrodes convert the ECG into electrical voltage, this voltage can be fed into an instrumentation amplifier, and then be processed. Analog Device AD624 instrumentation amplifier is choosen to amplify the ECG voltage from electrodes, which is in the range of several mV. The AD624 is set up with gain of 1000, and is supplied by +9 V and -9V battery power.

The input fed to the instrumentation amplifier is amplified using OTA which gives best amplification output rather than other amplifiers like operational and differential amplifiers. This amplified output is fed as input to the opto-coupler which is used for isolation purpose directs the amplified output to the band pass filter.

The filtered output is given to CRO through a probe to display the output amplified version of ECG signal. This whole process can be done physically like what was done in the above and also virtually by using virtual biomedical signal generator whose output is given to OTA and finally the amplified ECG signal can be seen through synthesized output waveforms which are implemented by specific commands using MATLAB software. However the amplification of those amplifiers are simulated through softwares like Mentor Graphics or Tanner EDA v16.0.
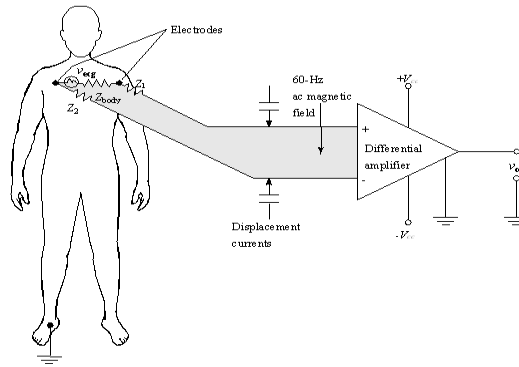
**Figure 2** Simplified ECG recording system

## 4. COMPARATIVE ANALYSIS OF AMPLIFIERS

Comparative analysis consisting of calculation of performance characteristics like amplification, gain, CMRR of different amplifiers like differential amplifier, operational amplifier, OTA are discussed in this topic.

### 4.1 Differential Amplifier:

A differential amplifier is a type of electronic amplifier that amplifies the difference between two input voltages but suppresses any voltage common to the two inputs. It is an analog circuit with two inputs $V_{in}^+$ and $V_{in}^-$ and one output $V_{out}$ in which the output is ideally proportional to the difference between the two voltages.
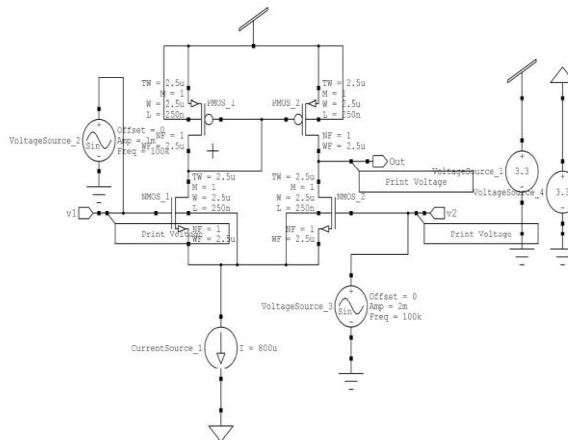
$V_{out} = A (V_{in}^+ + V_{in}^-)$



**Figure 3** Schematic of Differential Amplifier

### 4.1.1 Gain and CMRR Calculations

$A_d = 1/2 [R_3/(R_1 + R_3)][(R_4 + R_2)/R_2 + R_4/R_2]$

$A_{cm} = [R_3/(R_1 + R_3)] [(R_4 + R_2)/R_2 - R_4/R_2]$

Since $Rn = 1/g_{mn}$

$Gm = id/Vgs$

From the schematic, gm1=133.2uS, gds1= 2.21uS, gds4= 887 nS, gm6=1.567uS, gds6=7.475uS, gds7=44.07uS

Gain at first stage=gm1*(ro1 || ro4)  =gm1/(gds1+gds4) =0.15.

Gain at second stage= gm6/(gds6+gds7) =0.21

Common mode Gain= $A_{cm}$=Gain at first stage + Gain at second stage =0.36dB, CMRR (db)=20 log(Ad/Acm)  = 76dB

## 4.2 Operational Amplifier

Transistors M1, M2, M3, and M4 constitute the first stage of the op amp the differential amplifier. The gate of M1 is the non-inverting input and of M2 is the inverting input. A differential input signal is applied across the two input terminals will be amplified according to the gain of the differential stage. The gain of this stage is the transconductance of M1times the total output resistance seen at the drain of M2. The main resistances that contribute to the output resistance are that of the input transistors themselves and also the output resistance of the load transistors, M4 and M3.

The current mirror active load used in this circuit has three main advantages. First, these of active load devices create a large output resistance in a relatively small amount of chip area. The current mirror topology performs the differential to single- ended conversion of the input signal, and finally, the load helps with common mode rejection ratio.
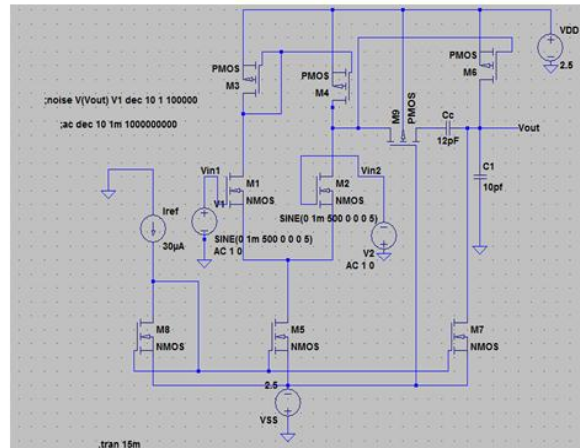


**Figure 4** Schematic of Operational Amplifier

In this, the conversion from differential to single ended is achieved by using a current mirror (M4 and M3). The current from M1 is mirrored by M3 and M4 and subtracted from the current from M2. Finally, the differential current from M1 and M2 multiplied by the output resistance of the input stage gives the single-ended output voltage, which is the part of the input to the next stage. The second stage is a current sink load inverter. The motive of the second gain stage is to provide additional gain consisting of transistors M6and M7. This stage receives the output from the drain of M2 and amplifies it through M6 by common source configuration. This stage employs an active device, M7, which serve as the load resistance for M6. The gain of this stage is the transconductance of M6 times the equivalent load resistance seen at the output of M6 and M7. M6 is the driver while M7 acts as load. Transistors M8 and a reference current source forma simple current mirror biasing network that provides a voltage between the gate and source of M5 andM7. Transistors M5 and M7 sink a current based on their gate to source voltage which is controlled by the bias network.

### 4.2.1 Gain and CMRR Calculations

Since $Rn=1/g_{mn}$

$Gm=id/Vgs$

From the schematic, $gm1=143uS$, $gds1=2.176uS$, $gds4= 912nS$, $gm6=1.467mS$, $gds6= 7.475$, $gds7=43.02uS$

Gain at first stage $=gm1*(ro_1 \parallel ro_4) =gm1/(gds1+gds4) =0.17$.

Gain at second stage $= gm6/(gds6+gds7) = 0.21$.

Common mode Gain $=A_{cm}=$ Gain at first stage + Gain at second stage $=0.38$.

CMRR (db) $=20 \log(Ad/Acm) = 59$ dB

### 4.3 Operational Transconductance Amplifier (OTA):

It is not always possible to restrict the range of input voltages in some practical applications. We can remove this limitation by a simple addition to the circuit.
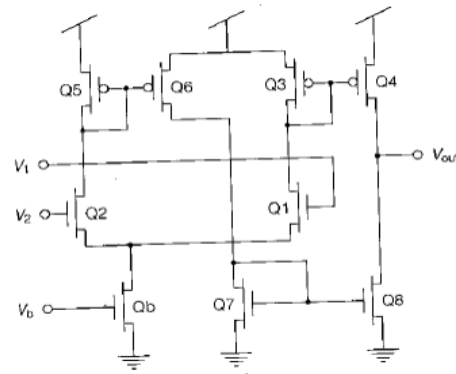
**Figure 5** Circuit of OTA

The major advantage of this trans-conductance amplifier is that the voltage swing is maximized i.e both the input and output voltages can go up to VDD and ground, without affecting the operation of the amplifier. The drain of Q2 is connected to the current mirror formed by Q5 and Q6 and the output is not fed directly. The currents from Q5 and Q6 are two halves of the current i differential pair. The current through Q6 is reflected through Q7 and Q8 and subtracted from I4 to form the output. The output current is just a difference of I1 and I2. This kind of Operation Trans-conductance amplifier is class of Wide range amplifiers. Also, the current mirrors (Q3 and Q5) hold the drain voltages of Q1 and Q2 nearly constant. Such wide range amplifiers have a gain of 10 times than that of a simple trans-conductance amplifier and much higher swing.
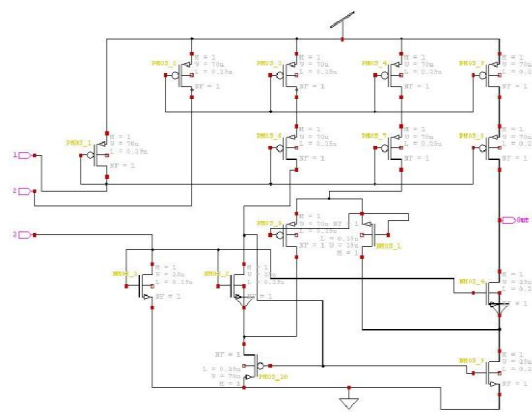


**Figure 6** Schematic of OTA

### 4.3.1 Gain and CMRR Calculations

Since $Rn=1/gmn$

$Gm=id/Vgs$

From the schematic, $gm1=153.4uS$, $gds1=133.2 uS$, $gds4=972nS$, $gm6=1.432uS$, $gds6=786uS$, $gds7=998.6uS$

Gain at first stage$=gm1*(ro1||ro4)$ $=gm1/(gds1+gds4)$ $=0.19$.

Gain at second stage$= gm6/(gds6+gds7)$ $=0.23$.

Common mode Gain$=Acm=$Gain at first stage + Gain at second stage $=0.42dB$

$CMRR(db)=20 log(Ad/Acm) = 124dB$

## 5. RESULTS AND DISCUSSION

This chapter deals with the experimental results with the help of photographs with detailed report at every level. Those experimental results consists of output waveforms of various amplifiers like differential amplifier, operational amplifier

and OTA that are generated from the respective amplfiers' schematics.

## 5.1 Differential Amplifier

### 5.1.1 Output Waveform

The given below waveform is the result of output voltage for a given differential input of 1 mv. The output is an amplified version of differential input with an amplification of 25 times of input. The output can be seen in any types of waveforms including sinusoidal, pulse, bitpulse.
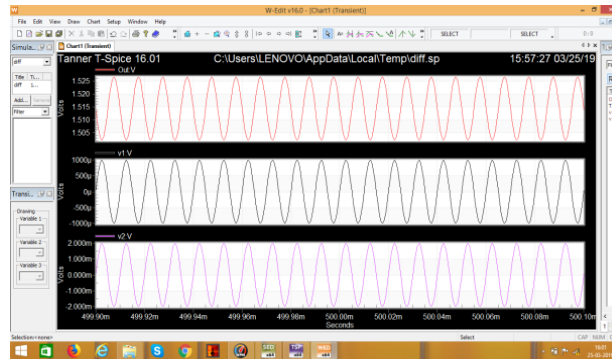


**Figure 7** Output Waveform of Differential Amplifier

### 5.1.2 Observations

Amplification: Vid=1mv→ Vout=25mv

Gain: 28dB

CMRR: 76 dB

## 5.2 Operational Amplifier

### 5.2.1Output Waveform

The given below waveform is the result of output voltage for a given differential input of 1 mv. The output is an amplified version of differential input with an amplification of 13 times of input. The output can be seen in any types of waveforms including sinusoidal, pulse, bit pulse.
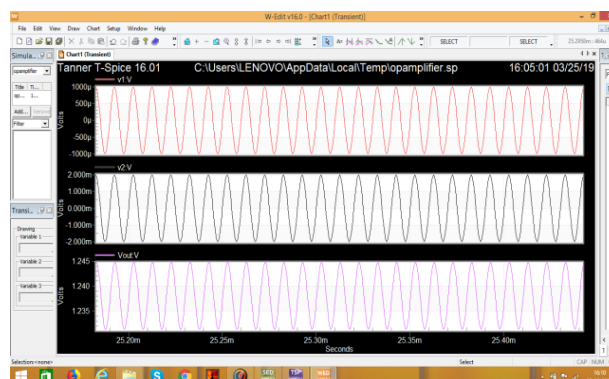


**Figure 8** Output Waveform of Operational Amplifier

### 5.2.2 Observations

Amplification: Vid=1mv→ Vout=13.5mv

Gain: 24dB

CMRR: 59 dB

### 5.3 Operational Trans conductance Amplifier (OTA)

### 5.3.1 Output Waveform

The given below waveform is the result of output voltage for a given differential input of 1 mv. The output is an amplified version of differential input with an amplification of 500 times of input which is the dominant of all of the given amplifiers. The output can be seen in any types of waveforms including sinusoidal, pulse, bit pulse.
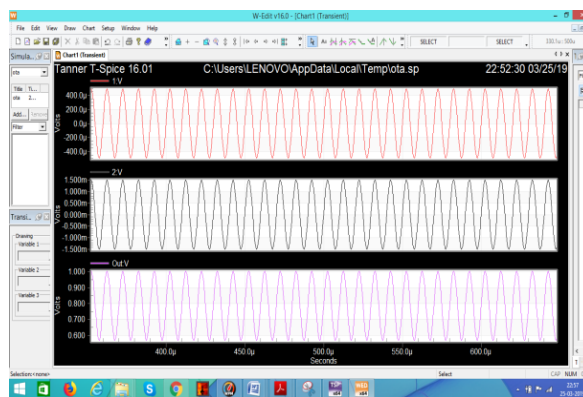


**Figure 8** Output Waveform of OTA

### 5.3.2 Observations

Amplification:Vid=1mv→Vout =500mv

Gain: 54dB

CMRR: 124 dB

| S.No. | Performance Parameter | Operational Amplifier | Differential Amplifier | Operational Transconductance Amplifier (OTA) |
|-------|----------------------|----------------------|-----------------------|---------------------------------------------|
| 1 | Amplification | 13.5mv | 25mv | 500mv |
| 2 | Gain | 24dB | 28dB | 54dB |
| 3 | CMRR | 59 dB | 76 dB | 124 dB |

**Figure 9** Comparison table of Performance Parameters

### 6. CONCLUSION AND FUTURE WORK

In this project, comparative analysis of amplifiers for better amplification of ECG signals is done. Among those amplifiers, this IA can be used in low power, low voltage. High CMRR applications are necessary for biomedical instruments. It is given by the CMOS Instrumentation amplifier using OTA. The common mode rejection ratio was found to be 124dB and power dissipation is 0.52mW. Therefore, finally the application of read-out circuit has high viability to be using in biomedical applications.

In this project various amplifiers are going to be examined in terms of amplification and DC gain to increase the performance of the amplifiers for biomedical applications. The advantages and disadvantages of OTA are discussed. Thus, further research would lead to a high performance Operational Transconductance Amplifier with increased gain and CMRR along with low power consumption with the help of OTA-CMFC (Capacitor Multiplier configuration with Frequency Compensation technique).

## ACKNOWLEDGMENTS

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