

# **THE DESIGN OF CALIBRATION CIRCUIT FOR ANALOG-TO-DIGITAL CONVERTER (ADC)**

**By**

**MOHAMMAD ARIF BIN S. MOHIDEEN ALI**

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## LIST OF ABBREVIATIONS

|        |  |
|--------|--|
| ADC:   | Analog-to-Digital Converter              |
| DAC:   | Digital-to-Analog Converter              |
| MDAC:  | Multiplying Digital-to-Analog Converter  |
| FA:    | Full Adder                               |
| DEC:   | Digital Error Correction                 |
| CMOS:  | Complementary metal-oxide semiconductor, |
| PMOS:  | P-type metal-oxide semiconductor         |
| NMOS:  | N-type metal-oxide semiconductor         |
| OPAMP: | Operational Amplifier                    |
| MUX:   | Multiplexer                              |
| DFF:   | D Flip-Flop                              |
| INL:   | Integral Non-Linearity                   |
| DNL:   | Differential Non-Linearity               |
| SNR:   | Signal-to-Noise Ratio                    |
| SINAD: | Signal-to-Noise-and-Distortion Ratio     |
| ENOB:  | Effective Number of Bits                 |
| PN:    | Pseudo-Random Number                     |
| MSB:   | Most Significant Bit                     |
| LSB:   | Least Significant Bit                    |
| GND:   | Ground                                   |
| AGND:  | Analog Ground                            |

## LIST OF NOTATIONS AND SYMBOLS

|              |                      |
|--------------|----------------------|
| $Q_e$ :      | Quantization Error   |
| $v_{IN}$ :   | Analog Input         |
| $V_{STEP}$ : | Discrete Output      |
| $N$ :        | Number of bits       |
| $V_{dd}$ :   | Drain Power Supply   |
| $V_{ss}$ :   | Source Power Supply  |
| $C_s$ :      | Sampling Capacitor   |
| $C_f$ :      | Feedback Capacitor   |
| $k$ :        | Boltzmann's Constant |
| $T$ :        | Absolute Temperature |
| $C$ :        | Capacitance          |

## ABSTRACT

Two types (Type 1 and Type 2) of calibration circuits for the pipelined ADC was designed using Verilog-A code modeling available from *ahdlib* Library of the Cadence Virtuoso tool. The modelling codes were modified to suit the proposed calibration circuit. Two identical pipelined ADC blocks (Pipelined ADC 1 and Pipelined ADC 2) were realized in 130nm Silterra CMOS process with each ADC having a 4-bit digital output respectively. A reference voltage of 600mV was used in the operation of the pipelined ADC with power supply connected to 1.2V for V<sub>dd</sub> and ground GND for V<sub>ss</sub>. The pipelined ADC operates at a sampling frequency of 2.2727MHz with input frequency from DC to 1.1364MHz. The input range voltage of the pipelined ADC is 300mV to 900mV with common-mode voltage of 600mV. Stages used in the construction of each pipelined ADCs employed Multiplying Digital-to-Analog Converter (MDAC) circuit architecture. The MDAC circuit is based on the 1.5-bit switched capacitor configuration with fully-differential operational amplifier (op-amp) gain or radix of approximately 2. A Digital Error Correction (DEC) was also proposed using Verilog-A code modeling where two blocks, time-align block and 4-bit adder made up the DEC block. No dithering signal or concept was used in the proposed calibration circuit, enabling the same MDAC circuit to be used with no modifications. A DNL of 0 LSB was achieved when calibration was enabled. The INL achieved by Calibration circuit type 1 is from maximum +1 LSB to minimum -1 LSB. For the Calibration circuit type 2, INL achieved is maximum +1 LSB and minimum 0 LSB. The DNL achieved by type 1 is from maximum 0 LSB to minimum -1 LSB while type 2 achieved 0 LSB.

## ABSTRAK

Dua jenis (Jenis 1 dan Jenis 2) litar tentukan untuk ADC saluran maklumat telah direka bentuk menggunakan kod Verilog-A yang boleh didapati daripada arkib *ahdlib* dari alat simulasi perisian Cadence Virtuoso. Kod yang diguna pakai telah diubahsuai bagi memenuhi litar tentukan yang dicadangkan. Dua blok ADC saluran maklumat yang sama (ADC saluran maklumat 1 dan ADC saluran maklumat 2) direalisasi menggunakan 130nm proses Silterra CMOS dengan setiap ADC mempunyai output digital 4-bit masing-masing. Voltan rujukan pada 600mV digunakan dalam operasi ADC saluran maklumat ini dengan bekalan kuasa 1.2V bagi Vdd dan 0V bagi Vss. ADC saluran maklumat beroperasi pada frekuensi pensampelan 2.2727MHz dengan frekuensi input dari DC ke 1.1364 MHz. Julat Voltan input ADC saluran maklumat adalah dari 300 mV ke 900 mV dengan voltan pertengahan pada 600 mV. Peringkat-peringkat saluran maklumat yang digunakan dalam pembinaan kedua-dua ADC saluran maklumat menggunakan litar Pendaraban Digital-ke-Analog Penukar (MDAC). Litar MDAC adalah berdasarkan kepada konfigurasi 1.5-bit suis-kapasitor dengan penguat kendalian (op-amp) pengamiran sepenuhnya yang mempunyai gandaan hampir 2. Pembetulan Ralat Digital (DEC) juga dicadangkan menggunakan kod Verilog-A pada dua blok, pengatur-masa dan penambah 4-bit. Tiada konsep pembetulan secara isyarat digunakan dalam litar tentukan yang dicadangkan, membolehkan litar MDAC yang sama digunakan tanpa pengubahsuaian. Pejana palsu-rawak (PN) tidak digunakan dalam litar tentukan yang dicadangkan. INL yang dicapai dengan tentukan jenis litar 1 adalah dari maksimum 1 LSB ke minimum -1 LSB . Untuk tentukan jenis litar 2 , INL yang dicapai adalah maksimum 1 LSB dan minimum 0 LSB . DNL yang dicapai dengan jenis 1 adalah dari maksimum 0 LSB ke minimum -1 LSB manakala jenis 2 mencapai 0 LSB .

## CHAPTER 1: INTRODUCTION

### 1.1 Background

Analog-to-digital converter (ADC) is commonly used in nearly all categories of electronic systems. In the real world application, most quantities surrounding us such as voice, image, pressure, temperature, and etc. are analog in nature. Processing such signals in its analog form by means of not using an ADC is challenging and costly which require analog signals to be first converted into digital signals. ADC converts the analog signals (voltages, currents) into its digital counterpart (normally binary), which then will be used extensively by a digital signal processor (DSP). Therefore, it is clearly known that the AD converters are indispensable parts and play important key role. This is the major motivation of research and design of AD converters. Application of ADCs are conversion of audio signals (mobile microphone, digital music records, etc.), conversion of video signals (cameras, frame grabber, etc.) and value acquisition measurement (temperature, pressure, luminance, etc.). In conclusion, the ADCs are indispensable interface between analog world and digital signal processors.

## 1.2 Problem Statement

Self-calibration in Analog-to-Digital Converters (ADC) has gain wide adaptation commonly due to the resolution and linearity improvement it offers. Calibration techniques on ADC are commonly categorized into two types; foreground calibration and background calibration.

In the foreground calibration, code errors at major code transitions are measured and stored during system start-up. Such technique lacks tracking capability when temperature and voltage supply tend to drift coupled with device aging. The background calibration instead tracks and calibrates at real time in the background during normal operation.

Initial calibration techniques were first conceived in analog. Calibration like the ratio independent algorithmic (P. W. Li, M. J. Chin, P. R. Gray, and R. Castello, 1984), reference updating (C. C. Shih and P. R. Gray, 1986), capacitor mismatch averaging (B.-S. Song, M. F. Tompset, and K. R. Lakshmi Kumar, 1988), on-chip capacitor trimming (M. de Wit, K. S. Tan, and R. K. Hester, 1993) and gain trimming (H. Ohara et. al., 1987) were all implemented in the analog domain. The major drawback of these analog calibration techniques is the complexity of circuit implementation. For example, capacitor based calibration would require the use of large array of capacitors to reduce capacitance mismatch and in gain based calibration complex modification on the operational amplifier (op-amp) is done to reduce gain offset. This increases the layout area tremendously of the calibration realization. Furthermore, the analog implementation of the calibration circuit tends to lower the conversion speed of the ADC block and is complex in circuit construction (Zhou Liren, Luo Lei, Ye Fan, Xu Jun, and Ren Junyan, 2009).

The digitally controlled self-calibration (H.-S. Lee, D. A. Hodges, and P. R. Gray, 1984) and digital-domain calibration (S.-H. Lee and B.-S. Song 1992) techniques were later proposed to alleviate the disadvantages of the analog calibration techniques but were developed more for Successive Approximation Register (SAR) ADC and Flash ADC, respectively.

In current trending, digital implementation of the calibration circuit are being researched extensively compared to its analog counterpart. Resolution of the pipelined ADC is limited by the accuracy of both the sub-ADC the sub-DAC being employ in each stage. Practically, pipelined ADC can achieve 10-bit resolution accuracy with no calibration and no trimming if stringent design and layout techniques (Cheongyuen Tsang, 2008) are practiced. However, to achieve resolution accuracy of higher than 10-bit, trimming or calibration is commonly adopted (Cheongyuen Tsang, 2008).

Most background calibration techniques employed on the pipelined ADC tend to be complex. Implemented in the digital domain, calibration techniques such as skip-and-fill algorithm with non-linear interpolation, sample-and-hold queue, Least-Mean-Square (LMS) adaptive algorithm, dithering based technique, LMS equalization method and etc. require large digital signal processing blocks. Such large digital signal processing blocks will need to be extensively verified for correct functionality and stringent timing requirements.

### **1.3 Objectives of Research**

Below are the primary objectives or goals that are desired to be achieved from this research, they are;

- To implement a proposed digital background calibration circuit for pipelined ADC architecture using Verilog-A code modeling.
- To achieve improvement on INL and DNL of pipelined ADC being integrated to the proposed digital background calibration circuit.
- To proof the workability and functionality of a calibration technique implemented using Verilog-A code modeling instead of Matlab modeling.

## 1.4 Scope of Research

Review on pipelined ADC need to be initiated to understand the working principles and fundamental sub-blocks that make up the pipelined ADC. Non-idealities need to be reviewed to understand its causes, sources, and mitigation steps that can be employed to reduce it. Few calibration approaches in reducing non-idealities need to be studied.

The pre-designed pipelined stage in 130 nm Silterra CMOS process will need to be analyzed on Cadence Virtuoso simulation tool to identify limitation towards exact specifications given and correct operation of the stage.

A Digital Error Correction (DEC) will be built to be integrated with the pipelined ADC. The pipelined ADC need to be constructed and validated to test the functionality of the DEC. Verilog-A code is to be used in the modeling of DEC.

Next, Calibration circuit will be built to be integrated the pipelined ADC. The DEC block is necessary in the functional validation of Calibration circuit. Performance verifications such as INL and DNL will be conducted to assess the improvement brought by the Calibration circuit



## **1.5 Contribution of Research**

A digital background calibration for the pipelined ADC from the mainstream is proposed. The concept of the calibration is proofed using Verilog-A coding for rapid prototype. Verilog-A code allows logic and analog block to be easily build and verified before venturing into real circuit design.

## **1.6 Thesis Outline**

Chapter 2 provides a brief overview of the operation of pipelined ADC, non-linearity errors or non-idealities in pipelined ADCs, performance indicators that involved in the measurement of non-linearity, and general overview of available calibration techniques.

In Chapter 3, a digital background calibration scheme realized on two pipelined ADC concept is proposed and implemented. Two types of Calibration circuit are introduced.

Chapter 4 proofs the functionality of the calibration concept through results and presents two performance indicators.

Chapter 5 concludes the presentation of this research and provides recommendations for future work.

## CHAPTER 2

### LITERATURE REVIEW

#### 2.1 Introduction

In this chapter, four different topology of ADCs are discussed in section 2.2; they are Integrating ADC, Flash ADC, Successive Approximation ADC, and Delta-Sigma ADC.

An overview on the relevant sub-blocks needed to construct a Pipelined stage and also the pipelined ADC using the stage are introduced in section 2.3. Fundamental operation of the whole Pipelined ADC are briefly explained.

Non-idealities such as comparator offset, finite op-amp gain, capacitor mismatch, and charge injection which occurs on the Pipelined ADC and the reason for calibration is needed is briefed in section 2.4.

Section 2.5 discusses on few performance indicators that determines the performance of the Pipelined ADC. Mentioned indicators are DNL, INL, SNR, and ENOB.

Finally in section 2.6, few published pipelined ADC calibration techniques and trending background calibration techniques are analyzed to note on design tradeoffs taken to integrate calibration circuit into their Pipelined ADC.

#### 2.2 ADC Architectures

Commonly, types of ADC topology is decided by the application purposes. The most important specification that decides the type of ADC topology which is suitable for the target application is the sampling speed. Sampling speed of ADC types is divided to four categories; they are slow, medium, fast, and oversampling. Resolution is another specification to take note when application specification is to meet.

### 2.2.1 Integrating ADC

The integrating ADC is distinctively implemented in two architectures; a single slope and a dual slope. Both of these ADCs fundamentally operates based on integrating a constant reference signal  $V_{REF}$ . Figure 2.1 shows this in the single-slope ADC implementation. The input signal  $v_{IN}$  is first sampled by an S/H circuit, the sampled input signal is then fed into positive input terminal of a comparator. The negative input terminal is connected to an integrator fed with a constant  $-V_{REF}$ , which basically generates a ramp signal. When  $v_{IN}$  is larger than the integrated signal, a counter starts to count the number of clock cycles. The counter stops counting when the integrator output voltage becomes equal to  $v_{IN}$ , resulting to a zero output terminal of the comparator ideally. Hence, the number of clock cycles is determined by difference between  $v_{IN}$  with  $-V_{REF}$ . However, integration constant variation due to how good matching of devices are practiced and temperature variation drifts the number of clock cycles. Furthermore, the accuracy of the single-slope ADC also depends on the linearity of the generated ramp.

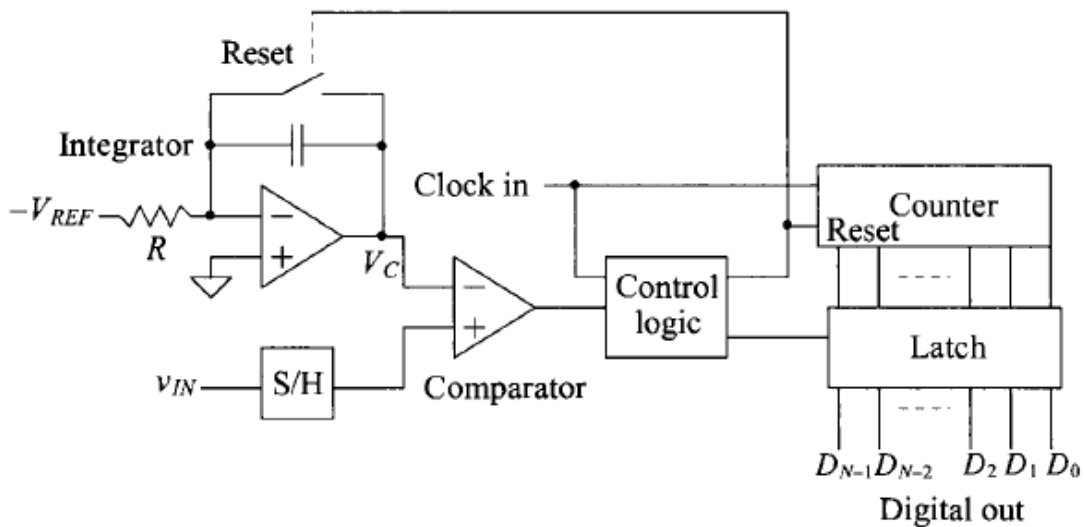


Figure 2.1: Block diagram of a single-slope Integrating ADC (R. JACOB BAKER, 2010, pg.

To mitigate the dependency of integration constant variation, double-slope architecture was introduced. In this ADC architecture, integration is performed on  $V_{REF}$  and  $v_{IN}$  which is two times integration as shown in Figure 2.2. The operation can be explained as follows; during the first phase,  $v_{IN}$  is integrated over  $N_{REF}$  clock cycles from a specific threshold voltage  $V_{TH}$  or 0V as shown in Figure 2.2 below. During the second phase, the integrator changes signal from  $v_{IN}$  to  $V_{REF}$  which second negative slope is generated. The second phase integration stops when the integrator signal is equal to 0V.

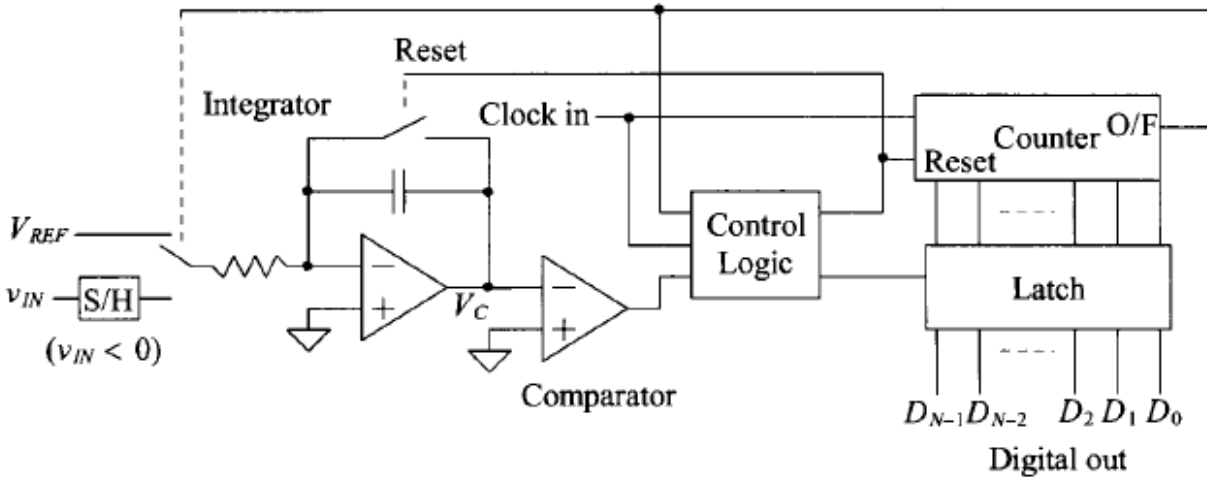


Figure 2.2: Block diagram of a dual-slope Integrating ADC (R. JACOB BAKER, 2010, pg. 1001)

The main drawback of both of these architectures is the long conversion time, which needs  $2^N T$  for a single slope and  $2^{N+1} T$  for dual slope where  $N$  and  $T$  represents number of bits and period of the clock. Therefore, these ADCs are normally employed in low conversion rate applications. However, using a time-to-digital converter as time measurement block, the conversion rate can be significantly improved to conversion rates up to several mega samples per second (E. Delagnes, D. Breton, F. Lugiez, and R. Rahmanifard, 2007; T. Fusayasu 2007).

High resolution, low power consumption and small layout footprint are primarily the advantages of these ADCs (O. Milgrome, S. Kleinfelder, and M. Levi, 1992). Such advantages allow integration of such ADCs in the design of a CMOS image sensors proposed by (O.-B. Kwon, K.-N. Park, D.-Y. Lee, K.-J. Lee, S.-C. Jun, C.-K. Kim, and W. Yang, 1999). Another integration is in multi-channel acquisition systems for nuclear measurements, where architecture except the integrating ADC does not meet layout area and power consumption expectations (E. Delagnes, D. Breton, F. Lugiez, and R. Rahmanifard, 2007; O. Milgrome, S. Kleinfelder, and M. Levi, 1992).

### **2.2.2 Flash ADC**

Flash converters can achieve very high sampling rates since the only fundamental building block is a comparator. The Flash ADC consists of  $2^{N-1}$  parallel connected comparators with each fed with different reference voltages as shown in Figure 2.3. Thermometer codes are generated from the comparators when analog input signal is fed, it has  $2^{N-1}$  bits corresponding to each comparator and each one show that the signal is above the corresponding reference level. A decoder is used to generate a more convenient representation at the output. The topology allows ADC to acquire very fast conversion time. However, flash ADCs are rarely implemented more than 8 bits (C. Lane, 1989). The main reason for this is the exponential increase of the number of comparators as the resolution increases. The number of comparators increases exponentially with the number of bits, so each additional bit in resolution requires a doubling of the number of comparators. As a result, the layout size and power consumption would be too large for higher resolutions.

Besides layout size and power consumption, design complexity also increase for higher resolutions. The area increase leads to difficulties in comparator matching, and clock and signal distribution. Furthermore, the power dissipation per unit area in an IC is limited. This means that as the number of transistors increases, the power consumption per single transistor should be minimized. This reduces the comparator bandwidth and analog bandwidth of the ADC as well.

Finally, the last disadvantage caused by the large number of comparators is the large input capacitance as the large number of comparators is connected to the input signal bus. This also puts constraints on the sample-and-hold circuit (if used) and leads to undesired bandwidth limitation. To reduce the number of comparators, and as a result the input signal load capacitance, a number of interpolation techniques can be used (P.-H. Chen and M. Peckerar, 2007).

Since comparator is the fundamental block, therefore its performance defines considerably performance of the ADC. Comparator offset (R. Plassche, 2003) is one of the performance limitation that degrades the ADC resolution. The offset can be minimized by increasing the gate size of the differential input stage of the comparator. This, however, leads to a larger input capacitive load. Offset averaging and auto-zeroing are alternative techniques that can be used in real time and discrete time ADCs respectively to solve offset issue, as well as special comparator structures (M. Wang and C.-I. Chen, 2007).

Propagation delay is another important performance parameter of a comparator which can be defined as the time taken when the analog signal has been applied to the comparator input and when a correct decision is produced at the comparator output. This delay should be smaller than the sampling period and failure to produce the result within the specified time can result to meta-stability, which causes distortion of the sampled signal and makes it difficult to recover the signal again. High conversion rates ADCs like the Flash ADC are commonly used in applications like wideband RF, optical communication, and video decoding.

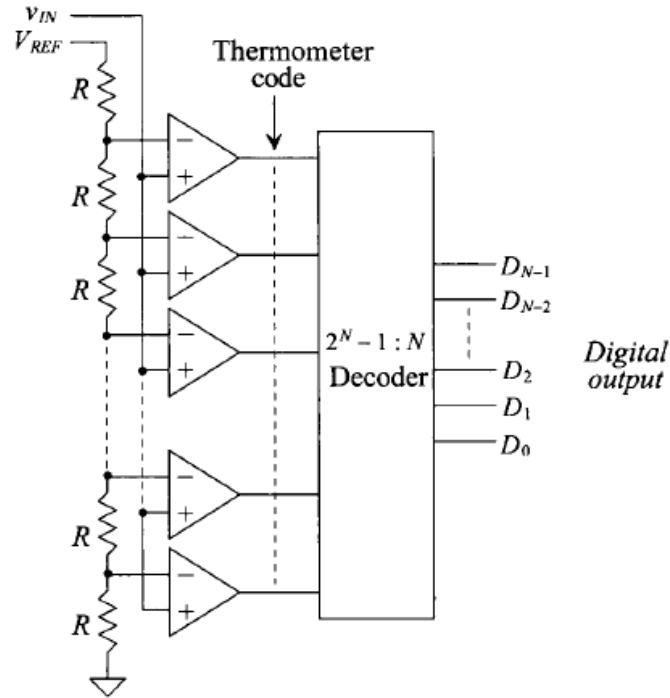


Figure 2.3: Block diagram of a Flash ADC (R. JACOB BAKER, 2010, pg. 986)

### 2.2.3 Successive Approximation ADC

The successive approximation ADC consists of a comparator, a N-bit Shift Register block, a successive approximation register (SAR) block, and a N-bit DAC block as shown in Figure 2.4. The input signal  $v_{IN}$  is sampled with an S/H circuit and fed into positive input terminal of the comparator. The SAR starts the first approximation by setting the MSB to 1 with assistance of the Shift Register. This digital combination is converted into analog representation by the DAC. The analog representation is then fed into negative input terminal of the comparator. Comparison is performed in order to determine the MSB value is stored, otherwise set to 0. When  $v_{IN}$  is larger than the analog representation, the MSB is stored. As SAR consists of N-bit, the exact operation is carried out on each bit in the SAR. After determining the last bit, the SAR generates an end of conversion (EOC) signal, and the digital representation of  $v_{IN}$  is completed.

Due to the requirement of  $N$  clock cycles to perform one conversion, where  $N$  equals the number of bits; this latency limits the conversion speed of the ADC. Besides that, having better resolution trades off a lower conversion rate. The conversion rate can be slightly improved by converting 2 bits in one clock cycle instead of one (K. Dabbagh-Sadeghipour, K. Hadidi, and A. Khoei, 2004). However, the ADC resolution is limited by the resolution of DAC, offset of the comparator and quantization noise of S/H circuit.

Significant power savings can be achieved using this type of ADC. Applications where power constraints are stringent but sampling rates are low, the type of ADC is particularly useful for examples sensor nodes and medical applications. With low complexity and a small number of devices, the die area is relatively low as well.

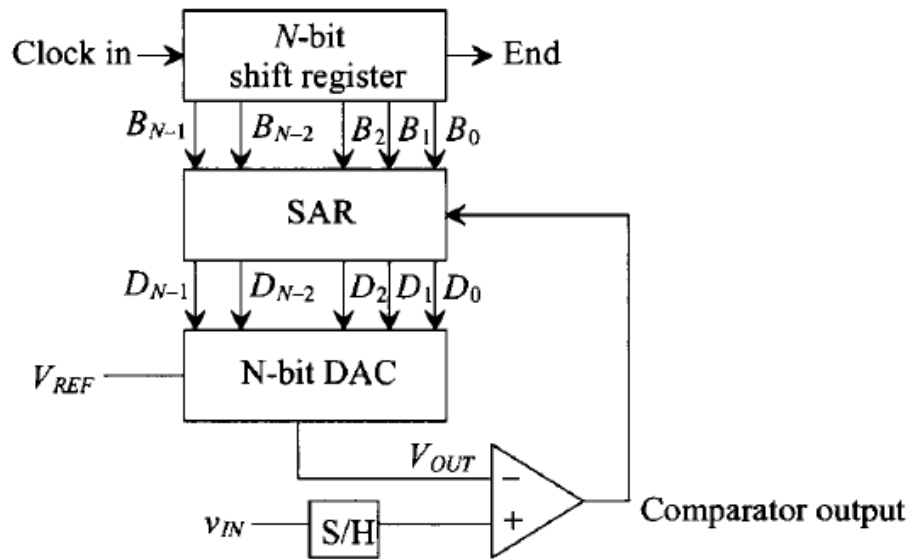


Figure 2.4: Block diagram of a Successive Approximation ADC (R. JACOB BAKER, 2010, pg. 1003)