DESIGN AND REALIZATION OF A HIGH-SPEED 12-BIT PIPELINED ANALOG / DIGITAL CONVERTER IP BLOCK

by

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DESIGN AND REALIZATION OF A HIGH-SPEED 12-BIT PIPELINED ANALOG / DIGITAL CONVERTER IP BLOCK

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To my parents,

my sister

and

to my Doc.
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Last, but by no means the least, I am grateful to my family for their patience and encouragement during my education. Finally, I am most indebted to Engin whose love; understanding and patience made it possible for me to be successful at the end.
DESIGN AND REALIZATION OF A HIGH-SPEED 12-BIT PIPELINED ANALOG / DIGITAL CONVERTER IP BLOCK

ABSTRACT

This thesis presents the design, verification, system integration and the physical realization of a monolithic high-speed analog-digital converter (ADC) with 12-bit accuracy. The architecture of the ADC has been realized as a pipelined structure consisting of four pipeline stages, each of which is capable of processing the incoming analog signal with 4-bit accuracy. A bit-overlapping technique has been employed for digital error correction between the pipeline stages so that the influence of possible errors that occur during analog signal processing can be minimized. The entire circuit architecture is built with a modular approach, consisting of identical blocks organized into an easily expandable pipeline chain.

All analog as well as digital sub-blocks of the ADC architecture presented in this work operate on a single clock signal (and its inverse), which significantly simplifies the design while ensuring a more robust performance. Other important features of this ADC include small area, single power supply, low power consumption, capability to operate at very high sampling clock rates, and the ability to handle a wide range of input signal amplitudes. The analog processing modules were designed using single-ended signals and the single-ended building blocks (as opposed to differential signals and building blocks) for simplicity. The ADC architecture was realized using a conventional 0.18 micron digital CMOS technology (Foundry: UMC), which ensures a lower overall cost and better portability for the design.

The ADC architecture presented in this work is capable of operating at sampling frequencies of up to 200 MHz, and still can achieve the nominal bit-resolution that was
intended for 12-bit accuracy. The entire circuit is designed with single 1.8 V power supply. The maximum range of the input signal amplitude that the ADC can handle is 1.6 Vpp, with 1.8 V supply voltage. The input signal range as well as the operating points of critical components can be adjusted externally using dedicated control pins. The overall power consumption is estimated as 67.5 mW at 200 MHz sampling rate. Each 4-bit pipeline stage consists of a 4-bit flash A/D converter, a fully capacitive multiplying DAC (MDAC) and the corresponding digital encoding circuitry. The overall silicon area of the ADC is approximately 0.25 mm².

The ADC architecture presented in this thesis is intended as a state-of-the-art data converter for very high-speed applications such as digital video transmission or high bandwidth wireless communication needs. It can be used either as a stand-alone single-chip unit, or as an embedded IP block that can be integrated with other modules on chip.
ÖZET

Bu tez, 12-bit doğrulukla çalışan bir monolitik yüksek hızlı analog-sayısal dönüştürücünün (ADC) tasarımı, sınınaması, sistem düzeyinde tümleştirilmesi ve fiziksel tasarımının gerçekleştirilmesi aşamalarından oluşmuştur. ADC’nin mimarisi, herhangi gelen analog işaret 4-bit doğrulukla işleyebilen dört kademeden oluşan bir veri yolu yapısı olarak gerçekleşmiştir. Analog işaret işlenmesi sırasında meydana gelebilecek olması hataların etkisini en aza indirebilmek amacı ile veri yolu kademeleri arasındaki sayısı hataları düzeltemek için bir bit-çalıştırma tekniği kullanılmıştır. Devrenin tüm mimarisi, benzer blokların kolayca genişletilebilir bir veriyolu zinciri biçiminde dizilmesinden oluşan, modüller bir yaklaşımla şekillendirilmiştir.

Bu çalışma kapsamında ele alınan ADC mimarisinin tüm analog ve sayısal alt-blokları, tasarım belirgin biçimde basitleştirilmiş ve aynı zamanda blokların daha güvenli olarak çalışmalarını sağlamak amacıyla, tek saat işaretleri (ve tersi) ile işlem yapıpabilecek şekilde tasarlanmıştır. Bu ADC’nin diğer önemli özellikleri arasında küçük kırık alan, tek güç kaynağı kullanılması, düşük güç gereksinimi, çok yüksek örnekleme hızlarında ve geniş bir giriş işaret genliği alanı içinde çalışabilme kabiliyeti sayılabilir. Çalışma kolaylığı nedeniyle, analog işlem modülleri, diferansiyel işaret ve yapısal bloklar yerine, tek uçlu işaretler ve tek sonlu yapısal bloklar kullanılarak tasarlanmıştır. Bu tezde sunulan ADC mimarisi, daha düşük toplam maliyet ve tasarım daha iyi taşınabilirlik sağlamak amacıyla, endüstride yaygın olarak kullanılan 0.18 mikron sayısal CMOS teknolojisi (Foundry: UMC) kullanılarak gerçekleştirilmiştir.
Tasarlanan dönüştürücü devresi, 200 MHz örnekleme frekansına kadar doğru çalışabilme ve bu yüksek örnekleme hızında hedeflenmiş olan 12-bit çözümürlüğü elde edebilme özelliklerine sahiptir. Devrenin tamamı bir tek 1.8 V güç kaynağı ile beslenebilecek şekilde tasarlanmıştır. ADC’nin 1.8 V besleme gerilimi ile işleyebileceğsi en yüksek giriş işaretli genliği (tepeden tepeye) 1.6 Vpp’dir. Giriş işaretli genliği ve bununla birlikte kritik modüllerin çalışma noktaları, denetleme girişleri yardımcıla dışarıdan ayarlanabilir. 200 MHz örnekleme hızında, toplam güç tüketimi 67.5 mW olarak öngörülmektedir. Her 4-bitlik veri yolu kademesi, bir adet 4-bit flash A/D dönüştürücü, bir adet tamamen kapasitif çarşıcı DAC (MDAC) ve bunlarla birlikte çalışacak sayısal çözümleyici devrelerden oluşmaktadır. ADC’nin toplam silikon alanı yaklaşık 0.25 mm²’dir.

Bu tez çalışmasında tasarlanan ADC mimarisi, sayısal görüntü iletimi veya yüksek bant genişliğine sahip telsiz haberleşme gereksinimleri gibi çok yüksek hız gerektiren uygulamalarda kullanılmak amacıyla tasarlanmıştır. Bu dönüştürücü, tek başına bir kırık olarak veya daha büyük bir kırık üzerine başka modüllerle birleştirilebilecek bir IP (intellectual property) bloğu olarak kullanılabilir.
TABLE OF CONTENTS

1 Introduction
   1.1 Serial A/D Converters.................................................................4
   1.2 Successive Approximation A/D Converters.....................................7
   1.3 Parallel A/D Converters..............................................................11

2 Performance Measures of Analog-to-Digital Converters 16
   2.1 Quantization Error ..........................................................16
   2.2 Quantization Noise ..........................................................17
   2.3 Dynamic Range ...............................................................18
   2.4 Resolution ........................................................................19
   2.5 Effective Number of Bits (ENOB) ...........................................19
   2.6 Differential Nonlinearity (DNL)..............................................19
   2.7 Integral Nonlinearity (INL) ..................................................20
   2.8 Absolute Accuracy ..........................................................22
   2.9 Gain Error .................................................................23
   2.10 Offset Error .................................................................24
   2.11 Transition Level ...........................................................24
   2.12 Monotonicity ................................................................26
   2.13 Missing Code ...............................................................26
   2.14 Differential Phase and Gain .............................................27
   2.15 Conversion Time and Sampling Rate ...................................27
   2.16 Sampling-Time Uncertainty .............................................28
   2.17 Input Bandwidth ...........................................................29
3 Pipelined Analog-to-Digital Converters 30
3.1 Pipelined Operation .................................................. 35
3.2 Circuit Implementation of a Pipeline Stage ..................... 41
3.3 Matlab Simulation Results ............................................ 42

4 Architecture Components: Voltage Comparator Design 51
4.1 Pipelined ADC Architecture Overview ............................. 51
4.2 Voltage Comparators: Basic Concepts ............................. 53
  4.2.1 Model of a voltage comparator .................................. 54
  4.2.2 Examples of CMOS comparator circuits ....................... 59
4.3 Examples of State-of-Art Voltage Comparators ................... 68
4.4 Proposed Voltage Comparator Architecture ....................... 74
  4.4.1 Basic comparator circuit ........................................ 74
  4.4.2 Full complementary voltage comparator ....................... 77
  4.4.3 Improved full complementary voltage comparator .......... 79
  4.4.4 Low power version of the complementary comparator ...... 93

5 Architecture Components: High-Speed Op-amp Design 95
5.1 Introduction of Basic Concepts .................................... 95
5.2 OTA Based Op-amp Design Flow .................................. 103
5.3 Inverter-Based Output Stage Frequency Analysis ................ 108
5.4 OTA Based High-Gain Op-amp Design .............................. 110
5.5 OTA Based Low-Gain Op-amp Design .............................. 120
5.6 OTA Based Op-amp Designed for Unity Gain Configuration .... 126

6 Design of ADC/MDAC Pipeline Stages 136
6.1 Design of the 4-Bit Flash A/D Converter ......................... 138
6.2 Digital-to-Analog Converter Design ............................... 144
  6.2.1 Current weighting D/A converter using ladder networks .. 145
  6.2.2 Self-calibrating D/A converters .............................. 146
  6.2.3 Voltage and charge-scaling D/A converters ................ 146
6.3 Error Correction with Bit-Overlapping .............................. 159
# List of Figures

1.1 Black box representation of an A/D converter ............................................. 3
1.2 Block diagram of single slope serial A/D converter ..................................... 4
1.3 Block diagram of a dual-slope A/D converter .............................................. 5
1.4 Waveforms of the dual-slope A/D converter in Figure 1.3 ......................... 6
1.5 Example of successive approximation A/D converter .................................. 7
1.6 The successive approximation process ....................................................... 8
1.7 Pipeline implementation of the algorithmic A/D converter ......................... 9
1.8 Implementation of the iterative, algorithmic A/D converter ....................... 10
1.9 A 3-bit, parallel (flash) A/D converter .................................................. 11
1.10 A time-interleaved A/D converter array ................................................ 12
1.11 Block representation of two-step flash A/D converter architecture ........... 12
1.12 Two-stages pipelined A/D converter configuration .................................. 13
1.13 Qualitative comparison of ADC techniques .......................................... 15
2.1 Input-output characteristics of an ideal 3-bit A/D converter and its quantization error ................................................................. 17
2.2 Illustration of DNL .................................................................................... 20
2.3 Illustration of INL for a 3-bit A/D converter ........................................... 21
2.4 Relation of DNL and INL ......................................................................... 22
2.5 Absolute accuracy is the summation of other error sources ...................... 23
2.6 Illustration of gain error ........................................................................... 24
2.7 Illustration of offset error .......................................................................... 25
2.8 Illustration of transition level .................................................................... 25
2.9 A nonmonotonic ADC transfer function ............................................... 26
2.10 An ADC transfer function with a missing code (100) ............................... 27
2.11 Illustration of sample period and conversion time .................................. 28
3.1 Typical two-step A/D converter architecture ............................................ 31
3.2 Multi-step A/D converter figure of performance illustration ................... 32
3.3 Multi-step A/D converter’s figure of performance illustration with internal amplification ................................................................. 33
3.4 A simple pipelined A/D converter architecture ........................................... 33
3.5 Implementation of i\textsuperscript{th} stage of a pipelined converter .................. 34
3.6 A pipelined A/D converter architecture model with offset and gain error for both the S/H amplifier and the residue amplifier .......................... 35
3.7 A 3-bit (1-bit per stage) pipelined A/D converter ........................................ 35
3.8 Implementation of each stage of Figure 3.7 .................................................. 35
3.9 The transfer function of the 1-bit stage shown in Figure 3.8 ......................... 36
3.10 Transfer function of 3-bit pipelined A/D converter ...................................... 36
3.11 Detailed transfer function characteristics ................................................... 37
3.12 Comparison of speed figure of merit, between Flash, 2-Step and Pipelined ADCs .................................................................................................................. 38
3.13 Comparison of power figure of merit, between Flash, 2-Step and Pipelined ADCs .................................................................................................................. 39
3.14 Implementation of i\textsuperscript{th} stage of a pipelined converter .................. 41
3.15 INL envelope obtained for different input voltage ranges ......................... 45
3.16 DNL envelope obtained for different input voltage ranges ....................... 46
3.17 INL envelope obtained for different resistor voltage variations ................. 46
3.18 DNL envelope obtained for different resistor voltage variations ............... 47
3.19 INL envelope obtained for different comparator offsets ......................... 47
3.20 DNL envelope obtained for different comparator offsets ......................... 48
3.21 INL envelope obtained for different supply voltage variations ................. 48
3.22 DNL envelope obtained for different supply voltage variations ............... 49
3.23 INL envelope obtained for combined parameter set simulations ............... 49
3.24 DNL envelope obtained for combined parameter set simulations .......... 50
4.1 Simplified block diagram of the proposed A/D converter architecture ........ 52
4.2 Detailed circuit architecture for one of the four proposed pipeline stages .... 52
4.3 Circuit symbol for a comparator ..................................................................... 54
4.4 Zero-order transfer curve of a comparator ................................................... 54
4.5 Zero-order model for a comparator ............................................................... 55
4.6 First-order transfer curve of a comparator .................................................. 56
4.7 First-order model of comparator .................................................................... 56
4.8 First-order transfer curve of a comparator including offset ...................... 57
4.9 First-order model of a comparator including offset. The ± sign of the offset voltage accounts for the fact that $V_{OS}$ is unknown in polarity ........... 57
4.10  Time domain response of a non-inverting first-order comparator    58
4.11  Current-sink inverter functioning as a comparator    59
4.12  DC transfer curve of simple comparator    59
4.13  Differential voltage comparator schematic    60
4.14  DC transfer curve of a differential voltage comparator    60
4.15  Two-stage voltage comparator    61
4.16  Comparator hysteresis curve    62
4.17  Comparator with hysteresis applied to the input differential stage only    63
4.18  (a) Comparator response to a noisy input (b) Comparator response to noisy input when hysteresis is added    63
4.19  (a) Circuit implementation of an auto-zeroed comparator (b) Comparator during φ₁ auto-zero state (c) Comparator during φ₂ state    64
4.20  A two-stage comparator that has a preamplifier and a positive-feedback track-and-latch state    65
4.21  A two-stage comparator    66
4.22  A two-stage comparator with capacitive coupling to eliminate input-offset voltage and clock-feedthrough errors along with positive-feedback for fast operation    67
4.23  The clock waveforms required by the comparator in Figure 4.22    67
4.24  A fully differential comparator with two nonoverlapping clocks by Lewis and Hurst    68
4.25  A comparator by Razavi and Wooley    69
4.26  A fully differential, high-speed voltage comparator    70
4.27  Timing information for the comparator given in Figure 4.26    71
4.28  Regeneration process small signal equivalent    72
4.29  Basic voltage comparator schematic    74
4.30  Output waveforms of basic voltage comparator circuit    75
4.31  Response time v.s input voltage difference    76
4.32  Response time variation along the entire input dynamic range for basic voltage comparator (V_{full-scale} = 1.8V)    77
4.33  Fully-complementary voltage comparator circuit diagram    78
4.34  Improved full complementary voltage comparator circuit    79
4.35  Response time of improved full complementary comparator with respect to input voltage difference    80
4.36 Response times of the improved full complementary voltage comparator, obtained for the entire input range ......................................................... 81
4.37 Response times obtained for different input voltage differences .................. 81
4.38 Power consumption for different input voltage differences .......................... 82
4.39 Power consumption for different sampling frequencies .............................. 82
4.40 Layout of the improved complementary-in voltage comparator .................... 83
4.41 Four bits ADC/MDAC schematic used in improved full complementary voltage comparator verification .......................................................... 84
4.42 Response times for Q, Q̅ and MDAC output voltage in ideal conditions .... 85
4.43 Response times obtained for input voltage at LSB level, typical corner and nMOS input stage transistor with mismatch ............................... 85
4.44 Response times obtained for input voltage at LSB level, typical corner and pMOS input stage transistor with mismatch ............................... 86
4.45 Response times obtained for input voltage at V_{full scale}/2 level, typical corner and nMOS input stage transistor with mismatch ........................ 86
4.46 Response times obtained for input voltage at V_{full scale} level, typical corner and pMOS input stage transistor with mismatch ........................ 87
4.47 Response times obtained for input voltage at MSB level, typical corner and nMOS input stage transistor with mismatch ............................... 87
4.48 Response times obtained for, typical corner simulations for 500 MHz clock frequency ...................................................................................... 88
4.49 Response times obtained for typical corner simulations for 750 MHz clock frequency ...................................................................................... 89
4.50 Response times obtained for typical corner simulations for 1 GHz clock frequency ...................................................................................... 89
4.51 Worst-case response time v.s input voltage in a simulated 4-bit ADC ....... 90
4.52 Average power dissipation of the comparator circuits vs. sampling frequency .......................................................................................... 91
4.53 Integral non-linearity obtained with improved full complementary comparator for typical simulation corner .................................................. 92
4.54 Differential non-linearity obtained with improved full complementary comparator for typical simulation corner .................................................. 92
5.23 Transient response of X2 feedback configuration to a 200 MHz
800 mV_pp input pulse signal ................................................................. 124
5.24 DC characteristics of unity gain stable OTA based op-amp .................. 127
5.25 Open loop AC characteristics of unity gain stable OTA based op-amp ...... 127
5.26 Closed loop AC characteristics of unity gain stable OTA based op-amp .... 128
5.27 Transient response of unity gain stable OTA based op-amp to a 200 MHz
10 mV_pp input pulse signal ........................................................................ 128
5.28 Block representation of sample-and-hold circuit .................................... 130
5.29 Block representation of residue amplifier ............................................ 130
5.30 Sampled voltage versus sampling pedestal, where input signal frequency
is 50 kHz and sampling clock frequency is 200 MHz.................................... 131
5.31 Sampled voltage versus held voltage, where input signal frequency is
50 kHz and sampling clock frequency is 200 MHz........................................ 131
5.32 Sampled voltage versus settling time, input signal frequency is 50 kHz
and sampling clock frequency is 200 MHz.................................................. 132
5.33 Sampled voltage versus sampling pedestal, where input signal frequency
is 30 MHz and sampling clock frequency is 200 MHz.................................... 132
5.34 Sampled voltage versus held voltage, where input signal frequency is
30 MHz and sampling clock frequency is 200 MHz........................................ 133
5.35 Sampled voltage versus settling time, input signal frequency is 30 MHz
and sampling clock frequency is 200 MHz.................................................. 133
5.36 Residue voltage obtained versus input voltage for typical simulation
corner.............................................................................................................. 134
5.37 Amplified residue voltage by X8 amplification factor............................... 134
6.1 Four stage pipelined A/D converter schematic. Ai and Bi bits are overflow
and underflow bits respectively. They will be explained in detail later in
this chapter .................................................................................................... 137
6.2 Simplified schematic of one stage of a 4-bit pipeline ADC ................. 137
6.3 DC input-output characteristics of a 4-bit pipeline A/D converter ....... 139
6.4 Typical corner DNL plot for the 4-bit pipeline A/D converter ............... 139
6.5 Typical corner INL plot for the 4-bit A/D converter .............................. 140
6.6 Typical FFT plot obtained for a 4-bit A/D converter when the input signal
frequency is 10 MHz and the sampling clock frequency is 300 MHz ............ 140
6.7 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 50 MHz to 300 MHz .......................................................... 142

6.8 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 500 MHz to 1.2 GHz .......................................................... 143

6.9 Overall variation of SNR as a function of the sampling frequency, with input signal frequency of 10 MHz .......................................................... 143

6.10 SNR of the 4-bit ADC as a function of input signal frequency, with sampling clock frequency of 200 MHz and the input signal frequency is varied from 10 MHz to 80 MHz .......................................................... 144

6.11 Ideal input-output characteristics for a three bit D/A converter .......................................................... 145

6.12 Implementation of a 3-bit voltage scaling D/A converter .......................................................... 147

6.13 N-bit charge-scaling D/A converter schematic .......................................................... 148

6.14 Schematic view of a 4-bit MDAC .......................................................... 151

6.15 Simplified cross-section representation of metal-metal capacitors constructed in N-well. Note that N-well is not shown in figure for simplicity .......................................................... 154

6.16 Residue voltages obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 200 MHz .......................................................... 156

6.17 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 200 MHz .......................................................... 157

6.18 Residue voltage obtained versus input voltage for typical simulation corner at 200 MHz sampling rate .......................................................... 157

6.19 Variation of the amplified residue voltage given Figure 6.19 as a function of the input voltage level, with X8 amplification factor .......................................................... 158

6.20 Residue voltage obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 50 MHz .......................................................... 158

6.21 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 50 MHz .......................................................... 159

6.22 Simplified schematic view of a 4-bit encoder block used in stage 1 .......................................................... 160

6.23 1-Bit-overlapping technique that is used in the design of the pipeline stages .......................................................... 161
7.1 Gate level schematic of the one-bit full-adder circuit ........................................ 165
7.2 Completely symmetric 1-bit full adder cell ......................................................... 166
7.3 Simulated input and output waveforms of 1-bit full adder circuit ......................... 166
7.4 Block diagram of a carry ripple adder chain consisting of n 1-bit
    full adders .............................................................................................................. 167
7.5 Layout view of the designed 1-bit full adder circuit ............................................. 169
7.6 CMOS implementation of the D-latch circuit ......................................................... 169
7.7 CMOS rising edge-triggered master-slave D flip-flop ............................................ 170
7.8 Simulated input and output waveforms of the CMOS DFF circuit given
    in Figure 7.7 ............................................................................................................ 171
7.9 Layout view of designed D-type flip-flop. Area is approximately
    132 µm² .................................................................................................................... 172
7.10 Gate level representation of XOR function ......................................................... 173
7.11 Full CMOS implementation of XOR function ...................................................... 174
7.12 Layout view of the designed XOR gate. Area is approximately 45 µm² .......... 175
7.13 Simulated input and output waveforms of the designed XOR circuit .............. 175
7.14 Simplified schematic view of a 4-bit encoder block ............................................ 176
8.1 Block level representation of four-stage pipelined A/D converter ..................... 178
8.2 Four-stage pipelined ADC clocking ................................................................. 178
8.3 Block level representation of the proposed clock distribution between
    functional modules of the pipelined ADC architecture .................................. 179
8.4 Assignment of clock signal / power distribution to different metal layers ...... 183
8.5 Lattice network consisting of clock and power distribution .............................. 183
8.6 Top-level floorplan of the designed 12-bit pipelined A/D converter .......... 184
LIST OF TABLES

1.1 Typical applications that require high-speed ADCs ........................................ 15
3.1 Pipelined A/D converter performance summary ............................................. 41
3.2 Parameter limit values applied to Matlab code ............................................ 43
3.3 Parameter limit values that will be used in input sitimuli for combined parameter set Matlab simulations .................................................. 43
3.4 Maximum and minimum values obtained for INL-DNL characteristics for each parameter ............................................................ 44
3.5 Maximum tolerable input parameter set ........................................................ 44
4.1 Design specifications of proposed pipelined A/D converter ............................ 51
5.1 Typical specifications of a CMOS op-amp ...................................................... 102
5.2 Aspect ratio table for high open loop-gain OTA .......................................... 112
5.3a Simulation results of the most important specifications ............................... 115
5.3b Comparison of simulated and manually calculated pole/zero frequencies .................................................................................. 116
5.4 Aspect ratio table for X8 OTA based op-amp configuration ............................ 117
5.5a Simulation results of the most important specifications ............................... 119
5.5b Comparison of simulated and manually calculated pole/zero frequencies ... 120
5.6 Aspect ratio table for low open loop-gain OTA ............................................. 121
5.7a Simulation results of the most important specifications ............................... 125
5.7b Comparison of simulated and manually calculated pole/zero frequencies ... 125
5.8 Element aspect ratios of unity gain stable OTA based op-amp ...................... 126
5.9a Simulation results of the most important specifications ............................... 129
5.9b Comparison of simulated and manually calculated pole/zero frequencies .................................................................................. 129
6.1 Encoding strategy of the related pipeline stage ............................................. 162
7.1 Truth table for the full adder circuit ............................................................. 164
7.2 Simulated carry_out dynamic performance results ....................................... 168
7.3 Simulated sum_out dynamic performance results ........................................ 168
7.4 Simulated dynamic characteristics of two-stage master-slave DFF circuit ................................................................. 172
7.5 Truth table of exclusive OR function ................................................................. 173
7.6 Simulated dynamic performance characteristics of XOR circuit .................. 174
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DESIGN AND REALIZATION OF A HIGH-SPEED 12-BIT PIPELINED ANALOG / DIGITAL CONVERTER IP BLOCK

ABSTRACT

This thesis presents the design, verification, system integration and the physical realization of a monolithic high-speed analog-digital converter (ADC) with 12-bit accuracy. The architecture of the ADC has been realized as a pipelined structure consisting of four pipeline stages, each of which is capable of processing the incoming analog signal with 4-bit accuracy. A bit-overlapping technique has been employed for digital error correction between the pipeline stages so that the influence of possible errors that occur during analog signal processing can be minimized. The entire circuit architecture is built with a modular approach, consisting of identical blocks organized into an easily expandable pipeline chain.

All analog as well as digital sub-blocks of the ADC architecture presented in this work operate on a single clock signal (and its inverse), which significantly simplifies the design while ensuring a more robust performance. Other important features of this ADC include small area, single power supply, low power consumption, capability to operate at very high sampling clock rates, and the ability to handle a wide range of input signal amplitudes. The analog processing modules were designed using single-ended signals and the single-ended building blocks (as opposed to differential signals and building blocks) for simplicity. The ADC architecture was realized using a conventional 0.18 micron digital CMOS technology (Foundry: UMC), which ensures a lower overall cost and better portability for the design.

The ADC architecture presented in this work is capable of operating at sampling frequencies of up to 200 MHz, and still can achieve the nominal bit-resolution that was
intended for 12-bit accuracy. The entire circuit is designed with single 1.8 V power supply. The maximum range of the input signal amplitude that the ADC can handle is 1.6 Vpp, with 1.8 V supply voltage. The input signal range as well as the operating points of critical components can be adjusted externally using dedicated control pins. The overall power consumption is estimated as 67.5 mW at 200 MHz sampling rate. Each 4-bit pipeline stage consists of a 4-bit flash A/D converter, a fully capacitive multiplying DAC (MDAC) and the corresponding digital encoding circuitry. The overall silicon area of the ADC is approximately 0.25 mm$^2$.

The ADC architecture presented in this thesis is intended as a state-of-the-art data converter for very high-speed applications such as digital video transmission or high bandwidth wireless communication needs. It can be used either as a stand-alone single-chip unit, or as an embedded IP block that can be integrated with other modules on chip.
ÖZET

Bu tez, 12-bit doğruylukla çalışan bir monolitik yüksek hızlı analog-sayısal dönüştürücünün (ADC) tasarımı, sınınamese, sistem düzeyinde tümleştirilmesi ve fiziyesel tasarımının gerçekleştirilmesi aşamalarından oluşmuştur. ADC’nin mimarisi, herhangi gelen analog işaretleri 4-bit doğruylukla işleyebilen dört kademeden oluşan bir veri yolu olarak gerçekleştirilmişdir. Analog işaret işlenmesi sırasında meydana gelebilecek olası hataların etkisini en aza indirebilmek amacı ile veri yolu kademeleri arasındaki sayısal hataları düzeltemek için bir bit-çalıştırma teknigi kullanılmıştır. Devrenin tüm mimarisi, benzer blokların kolayca genişletilebilir bir veri yolu zinciri biçiminde dizilmesinden oluşan, modüller bir yaklasıma şekillendirilmişdir.

Bu çalışma kapsamında ele alınan ADC mimarisinin tüm analog ve sayısal alt-blokları, tasarım belirgin biçimde basitleştirilmiş ve aynı zamanda blokların daha güvenli olarak çalışmalarını sağlamak amacıyla, tek saat işaretleri (ve tersi) ile işlem yapıabilecek şekilde tasarlanmıştır. Bu ADC’nün diğer önemli özellikleri arasında küçük kırık alan, tek güç kaynağı kullanılması, düşük güç gereksinimi, çok yüksek örnekleme hızlarında ve geniş bir giriş işaretleri genliği alanı içinde çalışabileceğini kabiliyeti sayılabilir. Çalışma kolaylığı nedeniyle, analog işlem modülleri, diferansiyel işaret ve yapısal bloklar yerine, tek uçlu işaretler ve tek sonlu yapısal bloklar kullanılarak tasarlanmıştır. Bu tezde sunulan ADC mimarisi, daha düşük toplam maliyet ve tasarım daha iyi taşınabilirlik sağlamak amacıyla, endüstride yaygın olarak kullanılan 0.18 mikron sayısal CMOS teknolojisi (Foundry: UMC) kullanılarak gerçekleştirilmişdir.
Tasarlanan dönüştürücü devresi, 200 MHz örnekleme frekansına kadar doğru çalışabilme ve bu yüksek örnekleme hızında hedeflenmiş olan 12-bit çözünürlüğü elde edebilme özelliklerine sahiptir. Devrenin tamamı bir tek 1.8 V güç kaynağı ile beslenebilecek şekilde tasarlanmıştır. ADC’nin 1.8 V besleme gerilimi ile işleyebileceği en yüksek giriş işaretili genliği (tepeden tepeye) 1.6 Vpp’dir. Giriş işaretili genliği ve bununla birlikte kritik modüllerin çalışma noktaları, denetleme girişleri yardımcıyla dışarıdan ayarlanabilir. 200 MHz örnekleme hızında, toplam güç tüketimi 67.5 mW olarak öngörülmektedir. Her 4-bitlik veri yolu kademesi, bir adet 4-bit flash A/D dönüştürücü, bir adet tamamen kapasitif çarşıcı DAC (MDAC) ve bunlarla birlikte çalışacak sayısal çözümleyici devrelerden oluşmaktadır. ADC’nin toplam silikon alanı yaklaşık 0.25 mm²’dir.

Bu tez çalışmasında tasarlanan ADC mimarisi, sayısal görüntü iletimi veya yüksek bant genişliğine sahip telsiz haberleşme gereksinimleri gibi çok yüksek hız gerektiren uygulamalarda kullanılmak amacıyla tasarlanmıştır. Bu dönüştürücü, tek başına bir kırmık olarak veya daha büyük bir kırmık üzerine başka modüllerle birleştirilebilecek bir IP (intellectual property) bloğu olarak kullanılabilir.
# TABLE OF CONTENTS

1 Introduction
   1.1 Serial A/D Converters ........................................... 4
   1.2 Successive Approximation A/D Converters ...................... 7
   1.3 Parallel A/D Converters ........................................ 11

2 Performance Measures of Analog-to-Digital Converters .......... 16
   2.1 Quantization Error ............................................. 16
   2.2 Quantization Noise ............................................ 17
   2.3 Dynamic Range ................................................ 18
   2.4 Resolution .................................................... 19
   2.5 Effective Number of Bits (ENOB) .............................. 19
   2.6 Differential Nonlinearity (DNL) ............................... 19
   2.7 Integral Nonlinearity (INL) .................................. 20
   2.8 Absolute Accuracy ............................................ 22
   2.9 Gain Error .................................................... 23
   2.10 Offset Error ................................................... 24
   2.11 Transition Level .............................................. 24
   2.12 Monotonicity .................................................. 26
   2.13 Missing Code .................................................. 26
   2.14 Differential Phase and Gain .................................. 27
   2.15 Conversion Time and Sampling Rate ........................... 27
   2.16 Sampling-Time Uncertainty ................................... 28
   2.17 Input Bandwidth .............................................. 29
# Design of Digital Building Blocks

7.1 Full Adder Design ................................................................. 163
    7.1.1 Single-bit adders ....................................................... 164
    7.1.2 Bit-parallel adder ..................................................... 167
7.2 D-type Flip-Flop (DFF) Design ........................................... 169
7.3 Exclusive OR Gate Design ................................................ 173

# Top-Level Construction of the Pipelined ADC

8.1 Overall Structure of the Pipeline ...................................... 177
8.2 Timing Considerations ...................................................... 179
8.3 General Floor-Planning and Layout Considerations ............... 181

# Conclusions

9 .................................................................................................. 186

**A** Literature Survey on Analog-to-Digital Converters .......... 189

**B** Complete Circuit Schematics and Mask Layouts ............... 201

**Bibliography** ........................................................................... 214
LIST OF FIGURES

1.1 Black box representation of an A/D converter ........................................ 3
1.2 Block diagram of single slope serial A/D converter .................................. 4
1.3 Block diagram of a dual-slope A/D converter ........................................... 5
1.4 Waveforms of the dual-slope A/D converter in Figure 1.3 .......................... 6
1.5 Example of successive approximation A/D converter ............................... 7
1.6 The successive approximation process .................................................... 8
1.7 Pipeline implementation of the algorithmic A/D converter ....................... 9
1.8 Implementation of the iterative, algorithmic A/D converter ...................... 10
1.9 A 3-bit, parallel (flash) A/D converter .................................................. 11
1.10 A time-interleaved A/D converter array ............................................... 12
1.11 Block representation of two-step flash A/D converter architecture ........ 12
1.12 Two-stages pipelined A/D converter configuration ............................... 13
1.13 Qualitative comparison of ADC techniques ........................................... 15
2.1 Input-output characteristics of an ideal 3-bit A/D converter and its quantization error ................................................................. 17
2.2 Illustration of DNL ................................................................................. 20
2.3 Illustration of INL for a 3-bit A/D converter .......................................... 21
2.4 Relation of DNL and INL ...................................................................... 22
2.5 Absolute accuracy is the summation of other error sources .................... 23
2.6 Illustration of gain error ......................................................................... 24
2.7 Illustration of offset error ....................................................................... 25
2.8 Illustration of transition level .................................................................. 25
2.9 A nonmonotonic ADC transfer function ................................................. 26
2.10 An ADC transfer function with a missing code (100) ............................. 27
2.11 Illustration of sample period and conversion time .................................. 28
3.1 Typical two-step A/D converter architecture ............................................ 31
3.2 Multi-step A/D converter figure of performance illustration .................... 32
3.3 Multi-step A/D converter's figure of performance illustration with internal amplification .............................................................. 33
3.4 A simple pipelined A/D converter architecture ........................................... 33
3.5 Implementation of i-th stage of a pipelined converter .................................... 34
3.6 A pipelined A/D converter architecture model with offset and gain error
   for both the S/H amplifier and the residue amplifier ...................................... 35
3.7 A 3-bit (1-bit per stage) pipelined A/D converter ........................................ 35
3.8 Implementation of each stage of Figure 3.7 .................................................. 35
3.9 The transfer function of the 1-bit stage shown in Figure 3.8 ......................... 36
3.10 Transfer function of 3-bit pipelined A/D converter ...................................... 36
3.11 Detailed transfer function characteristics ................................................... 37
3.12 Comparison of speed figure of merit, between Flash, 2-Step and
   Pipelined ADCs .............................................................................................. 38
3.13 Comparison of power figure of merit, between Flash, 2-Step and
   Pipelined ADCs .............................................................................................. 39
3.14 Implementation of i-th stage of a pipelined converter .................................... 41
3.15 INL envelope obtained for different input voltage ranges .............................. 45
3.16 DNL envelope obtained for different input voltage ranges ............................ 46
3.17 INL envelope obtained for different resistor voltage variations .................... 46
3.18 DNL envelope obtained for different resistor voltage variations .................... 47
3.19 INL envelope obtained for different comparator offsets ............................... 47
3.20 DNL envelope obtained for different comparator offsets ............................... 48
3.21 INL envelope obtained for different supply voltage variations ..................... 48
3.22 DNL envelope obtained for different supply voltage variations ..................... 49
3.23 INL envelope obtained for combined parameter set simulations .................... 49
3.24 DNL envelope obtained for combined parameter set simulations ................. 50
4.1 Simplified block diagram of the proposed A/D converter architecture ............ 52
4.2 Detailed circuit architecture for one of the four proposed pipeline stages ....... 52
4.3 Circuit symbol for a comparator ...................................................................... 54
4.4 Zero-order transfer curve of a comparator ...................................................... 54
4.5 Zero-order model for a comparator .................................................................. 55
4.6 First-order transfer curve of a comparator ...................................................... 56
4.7 First-order model of comparator ..................................................................... 56
4.8 First-order transfer curve of a comparator including offset ........................... 57
4.9 First-order model of a comparator including offset. The ± sign of the
   offset voltage accounts for the fact that \( V_{OS} \) is unknown in polarity .......... 57
4.36 Response times of the improved full complementary voltage comparator, obtained for the entire input range ................................................................. 81
4.37 Response times obtained for different input voltage differences .......... 81
4.38 Power consumption for different input voltage differences ................. 82
4.39 Power consumption for different sampling frequencies ....................... 82
4.40 Layout of the improved complementary-in voltage comparator .......... 83
4.41 Four bits ADC/MDAC schematic used in improved full complementary voltage comparator verification ................................................................. 84
4.42 Response times for \( Q \), \( \overline{Q} \) and MDAC output voltage in ideal conditions .... 85
4.43 Response times obtained for input voltage at LSB level, typical corner and nMOS input stage transistor with mismatch ............................................. 85
4.44 Response times obtained for input voltage at LSB level, typical corner and pMOS input stage transistor with mismatch ............................................. 86
4.45 Response times obtained for input voltage at \( V_{\text{full scale}}/2 \) level, typical corner and nMOS input stage transistor with mismatch ............................................. 86
4.46 Response times obtained for input voltage at \( V_{\text{full scale}} \) level, typical corner and pMOS input stage transistor with mismatch ............................................. 87
4.47 Response times obtained for input voltage at MSB level, typical corner and nMOS input stage transistor with mismatch ............................................. 87
4.48 Response times obtained for, typical corner simulations for 500 MHz clock frequency ......................................................................................... 88
4.49 Response times obtained for typical corner simulations for 750 MHz clock frequency ......................................................................................... 89
4.50 Response times obtained for typical corner simulations for 1 GHz clock frequency ......................................................................................... 89
4.51 Worst-case response time v.s input voltage in a simulated 4-bit ADC .... 90
4.52 Average power dissipation of the comparator circuits v.s. sampling frequency ............................................................................................... 91
4.53 Integral non-linearity obtained with improved full complementary comparator for typical simulation corner ....................................................... 92
4.54 Differential non-linearity obtained with improved full complementary comparator for typical simulation corner ....................................................... 92
4.55 Comparator circuit with latched output stage during reset mode (Low power comparator version) .............................................................. 93
5.1 Input and output waveforms of a conventional sample-and-hold amplifier illustrating some possible errors ........................................... 96
5.2 Behavioral model for ideal differential input, single-ended output op-amp ......................................................................................... 98
5.3 A model for an ideal op-amp showing some of the nonideal characteristics .................................................................................. 99
5.4 Typical frequency response for an op-amp ........................................ 100
5.5 The differential OTA symbol and ideal model .................................. 103
5.6 Symmetrical CMOS OTA schematic .................................................. 104
5.7 Inverter-based output stage schematic .............................................. 108
5.8 Simplified small signal equivalent of the inverter ............................... 109
5.9 Equivalent circuit of Figure 5.8 .......................................................... 109
5.10 High open loop-gain OTA based op-amp schematic .......................... 112
5.11 DC characteristics of high open loop-gain OTA based op-amp .......... 113
5.12 Open loop AC characteristics of high open loop-gain OTA based op-amp ...................................................................................... 114
5.13 Closed loop AC characteristics of high open loop-gain OTA based op-amp ................................................................................. 114
5.14 Transient characteristics of high open loop-gain OTA used in X16 feedback gain for residue amplifier for a 200 MHz 100 mV_{pp} input pulse ................................................................. 115
5.15 DC characteristics of X8 OTA based op-amp .................................... 117
5.16 Open loop AC characteristics of X8 OTA based op-amp .................. 118
5.17 Closed loop AC characteristics of X8 OTA based op-amp ................. 118
5.18 Transient response of X8 OTA based op-amp to a 200 MHz 100 mV_{pp} input pulse ........................................................................... 119
5.19 Schematic view of low open loop-gain OTA .................................... 121
5.20 DC characteristics of low open loop-gain OTA based op-amp ............ 123
5.21 Open loop AC characteristics of low open loop-gain OTA based op-amp ...................................................................................... 123
5.22 Closed loop AC characteristics of low open loop gain OTA based op-amp ...................................................................................... 124
5.23 Transient response of X2 feedback configuration to a 200 MHz
800 mV<sub>pp</sub> input pulse signal ................................................................. 124
5.24 DC characteristics of unity gain stable OTA based op-amp ....................... 127
5.25 Open loop AC characteristics of unity gain stable OTA based op-amp ........ 127
5.26 Closed loop AC characteristics of unity gain stable OTA based op-amp ....... 128
5.27 Transient response of unity gain stable OTA based op-amp to a 200 MHz
10 mV<sub>pp</sub> input pulse signal .................................................................... 128
5.28 Block representation of sample-and-hold circuit ....................................... 130
5.29 Block representation of residue amplifier .................................................. 130
5.30 Sampled voltage versus sampling pedestal, where input signal frequency
is 50 kHz and sampling clock frequency is 200 MHz ..................................... 131
5.31 Sampled voltage versus held voltage, where input signal frequency is
50 kHz and sampling clock frequency is 200 MHz ....................................... 131
5.32 Sampled voltage versus settling time, input signal frequency is 50 kHz
and sampling clock frequency is 200 MHz .................................................. 132
5.33 Sampled voltage versus sampling pedestal, where input signal frequency
is 30 MHz and sampling clock frequency is 200 MHz .................................. 132
5.34 Sampled voltage versus held voltage, where input signal frequency is
30 MHz and sampling clock frequency is 200 MHz ..................................... 132
5.35 Sampled voltage versus settling time, input signal frequency is 30 MHz
and sampling clock frequency is 200 MHz .................................................. 133
5.36 Residue voltage obtained versus input voltage for typical simulation
corner ............................................................................................................. 134
5.37 Amplified residue voltage by X8 amplification factor .................................. 134
6.1 Four stage pipelined A/D converter schematic. Ai and Bi bits are overflow
and underflow bits respectively. They will be explained in detail later in
this chapter .................................................................................................... 137
6.2 Simplified schematic of one stage of a 4-bit pipeline ADC .......................... 137
6.3 DC input-output characteristics of a 4-bit pipeline A/D converter .............. 139
6.4 Typical corner DNL plot for the 4-bit A/D converter .................................. 139
6.5 Typical corner INL plot for the 4-bit A/D converter .................................... 140
6.6 Typical FFT plot obtained for a 4-bit A/D converter when the input signal
frequency is 10 MHz and the sampling clock frequency is 300 MHz .......... 140
6.7 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 50 MHz to 300 MHz ................................................................. 142
6.8 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 500 MHz to 1.2 GHz ................................................................. 143
6.9 Overall variation of SNR as a function of the sampling frequency, with input signal frequency of 10 MHz ................................................................. 143
6.10 SNR of the 4-bit ADC as a function of input signal frequency, with sampling clock frequency of 200 MHz and the input signal frequency is varied from 10 MHz to 80 MHz ................................................................. 144
6.11 Ideal input-output characteristics for a three bit D/A converter .......... 145
6.12 Implementation of a 3-bit voltage scaling D/A converter .................. 147
6.13 N-bit charge-scaling D/A converter schematic .................................. 148
6.14 Schematic view of a 4-bit MDAC ....................................................... 151
6.15 Simplified cross-section representation of metal-metal capacitors constructed in N-well. Note that N-well is not shown in figure for simplicity .................. 154
6.16 Residue voltages obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 200 MHz ................................................................. 156
6.17 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 200 MHz ................................................................. 157
6.18 Residue voltage obtained versus input voltage for typical simulation corner at 200 MHz sampling rate ................................................................. 157
6.19 Variation of the amplified residue voltage given Figure 6.19 as a function of the input voltage level, with X8 amplification factor ................................................................. 158
6.20 Residue voltage obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 50 MHz ................................................................. 158
6.21 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 50 MHz ................................................................. 159
6.22 Simplified schematic view of a 4-bit encoder block used in stage 1 .......... 160
6.23 1-Bit–overlapping technique that is used in the design of the pipeline stages ................................................................. 161
7.1 Gate level schematic of the one-bit full-adder circuit ........................................ 165
7.2 Completely symmetric 1-bit full adder cell ....................................................... 166
7.3 Simulated input and output waveforms of 1-bit full adder circuit .......................... 166
7.4 Block diagram of a carry ripple adder chain consisting of n 1-bit full adders .......... 167
7.5 Layout view of the designed 1-bit full adder circuit .......................................... 169
7.6 CMOS implementation of the D-latch circuit ..................................................... 169
7.7 CMOS rising edge-triggered master-slave D flip-flop ........................................ 170
7.8 Simulated input and output waveforms of the CMOS DFF circuit given in Figure 7.7 ........................................................................................................ 171
7.9 Layout view of designed D-type flip-flop. Area is approximately 132 µm² .............. 172
7.10 Gate level representation of XOR function ......................................................... 173
7.11 Full CMOS implementation of XOR function ..................................................... 174
7.12 Layout view of the designed XOR gate. Area is approximately 45 µm² .......... 175
7.13 Simulated input and output waveforms of the designed XOR circuit ............... 175
7.14 Simplified schematic view of a 4-bit encoder block ......................................... 176
8.1 Block level representation of four-stage pipelined A/D converter ....................... 178
8.2 Four-stage pipelined ADC clocking ..................................................................... 178
8.3 Block level representation of the proposed clock distribution between functional modules of the pipelined ADC architecture ........................................ 179
8.4 Assignment of clock signal / power distribution to different metal layes .......... 183
8.5 Lattice network consisting of clock and power distribution .............................. 183
8.6 Top-level floorplan of the designed 12-bit pipelined A/D converter .................... 184
LIST OF TABLES

1.1 Typical applications that require high-speed ADCs ........................................ 15
3.1 Pipelined A/D converter performance summary ............................................. 41
3.2 Parameter limit values applied to Matlab code ............................................. 43
3.3 Parameter limit values that will be used in input sitimuli for combined parameter set Matlab simulations ......................................................... 43
3.4 Maximum and minimum values obtained for INL-DNL characteristics for each parameter ................................................................. 44
3.5 Maximum tolerable input parameter set .......................................................... 44
4.1 Design specifications of proposed pipelined A/D converter .............................. 51
5.1 Typical specifications of a CMOS op-amp ..................................................... 102
5.2 Aspect ratio table for high open loop-gain OTA ........................................... 112
5.3a Simulation results of the most important specifications ................................. 115
5.3b Comparison of simulated and manually calculated pole/zero frequencies ............ 116
5.4 Aspect ratio table for X8 OTA based op-amp configuration ........................... 117
5.5a Simulation results of the most important specifications ................................ 119
5.5b Comparison of simulated and manually calculated pole/zero frequencies ............ 120
5.6 Aspect ratio table for low open loop-gain OTA ............................................. 120
5.7a Simulation results of the most important specifications ................................ 125
5.7b Comparison of simulated and manually calculated pole/zero frequencies ............ 125
5.8 Element aspect ratios of unity gain stable OTA based op-amp ......................... 126
5.9a Simulation results of the most important specifications ................................ 129
5.9b Comparison of simulated and manually calculated pole/zero frequencies ............ 129
6.1 Encoding strategy of the related pipeline stage ............................................. 162
7.1 Truth table for the full adder circuit ............................................................ 164
7.2 Simulated carry_out dynamic performance results ........................................ 168
7.3 Simulated sum_out dynamic performance results .......................................... 168
7.4 Simulated dynamic characteristics of two-stage master-slave DFF circuit ................................................................. 172
7.5 Truth table of exclusive OR function ......................................................... 173
7.6 Simulated dynamic performance characteristics of XOR circuit ............... 174
1. INTRODUCTION

Our physical world produces a vast variety of analog signals, while most of the signal processing systems operate exclusively on digital signals. Consequently, it is necessary to be able to convert back and forth between the two types of signals. Therefore analog-to-digital and digital-to-analog converters are an important part of a signal processing system. From this point of view a state of art, four stage pipelined analog-to-digital converter using flash algorithm is proposed and discussed in detail in this thesis. The thesis is organized as follows: Chapter 1 includes a brief summary of A/D converter topologies. In Chapter 2 performance measures of A/D converters, such as INL, DNL etc. are examined. Chapter 3 introduces the concept of the proposed pipelined ADC architecture in detail. Chapter 4 and Chapter 5 handles the building blocks of proposed ADC such as comparators and sample-hold amplifiers respectively; in Chapter 6 assembling a 4-bit pipeline stage is introduced and Chapter 7 reviews the digital building blocks. Then Chapter 8 introduces the four stage pipelined ADC. Finally conclusions are presented in Chapter 9.

The objective of an A/D (analog-to-digital) converter is to determine the digital output corresponding to an analog input signal. In other words, an Analog-to-Digital converter is a device that converts a continuous range of input amplitude levels into a discrete finite set of digital outputs. In this chapter, the fundamental aspects of Analog-to-Digital converters with different architectures are presented, in order to establish the basic classification of ADCs.
Analog-to-Digital converter architectures can be classified on the basis of the sequence of operations used to digitally encode an analog input. At the top of this classification hierarchy, converters are partitioned into two groups, Nyquist-Rate ADCs and Oversampling ADCs, based on the rate at which the input signals sampled relative to its bandwidth.

- **Nyquist-rate Converters**: We loosely define Nyquist-Rate data converters as those converters that generate a series of output values in which each value has one-to-one correspondence with a single input value. However, it should be noted that Nyquist-Rate converters are seldom used at the Nyquist-Rate due to the difficulty in realizing practical anti-aliasing real reconstruction filters. In most cases, Nyquist-Rate converters operate at 1.5 to 10 times the Nyquist-Rate (i.e., 3 to 20 times the input signal’s bandwidth. As a summary, Nyquist-Rate converters:

  * Can digitize input signals with bandwidths approaching half the sampling rate
  * Operate at or near the minimum sampling rate for a given input bandwidth
  * Ensure that each sample is quantized to the full precision of the converter, i.e., the quantization error is minimized for each individual sample [2].

- **Oversampling Converters**: Oversampling converters are those converters that operate much faster than the input signal’s Nyquist-Rate (typically 20 to 512 times faster) and increase the output’s signal-to-noise (SNR) by filtering output quantization noise that is not in the signal’s bandwidth. In A/D converters, this filtering is performed digitally. Most often, oversampling converters use noise shaping to place much of the quantization noise outside the input signal’s bandwidth. Thus, the main characteristics of oversampling converters are as follows:

  * Sample signals at rates well above the signal bandwidth.
  * Digital encoding obtained by digitally “averaging” sequence of samples encoded at the oversampling rate.
* Coarse amplitude quantization is combined with feedback and digital filtering to obtain a precise estimate of the input.
* Minimize quantization error power in sequence of samples rather than in a single sample; therefore must use metrics like SNR and mean squared baseband error, not INL or DNL [2].

The block diagram representation of an A/D Converter is shown in Figure 1.1, where \( B_{\text{out}} \) is the digital output word while \( V_{\text{in}} \) and \( V_{\text{ref}} \) are the analog input and reference signals respectively. Also, we define \( V_{L\text{SB}} \) to be the signal variation corresponding to a single LSB change.

![Block diagram of A/D Converter](image)

**Figure 1.1 Black box representation of an A/D converter.**

For an A/D converter, the following equation relates these signals as,

\[
V_{\text{ref}}(b_1 2^{-1} + b_2 2^{-2} + \ldots + b_N 2^{-N}) = V_{\text{in}} = V_{x}
\]

where

\[
\frac{-\sqrt{2}V_{L\text{SB}}}{2} < V_{x} < \frac{\sqrt{2}V_{L\text{SB}}}{2}
\]

(1.1)

and \( V_{x} \) represents the quantization error, which will be explained in the next chapter. Note that there is now a range of valid input values that produce the same digital output word. It should be noted that the relation shown above holds only if the input signal remains within 1LSB of the two last transition voltages.

After examining the ideal analog-to-digital converter, this section follows with the brief explanations of the types of A/D Converters, such as the serial, successive
approximation, parallel (flash) and high performance A/D converters, which are under the Nyquist-rate converter branch.

1.1 Serial A/D Converters

This type of converters performs serial sequential operations in time domain until the conversion is complete. Two architectures can be examined, called the single-slope and dual-slope. These are level-at-a-time integrating converters where input is converted to a timing pulse as “pulswidth modulating" converters and the width of this pulse is measured by counting clock cycles (also referred to as “pulse-width modulating” converters). Offering high resolution and accuracy but slow conversion speed ($2^N$ clock/sample), these types of converters are used in applications of high resolution, low frequency.

Figure 1.2 Block diagram of a single slope serial A/D converter [3].

Figure 1.2 shows the block diagram of a single-slope serial A/D converter. This type of converter consists of a ramp generator, an internal counter, a comparator, an AND gate, and a counter that generates the output digital code. At the beginning of a conversion cycle the analog input is sampled, held and applied to the positive terminal of the comparator. The counters are reset, and a clock is applied to both the time interval counter and the AND gate. On the first clock pulse, the ramp generator begins to integrate the reference voltage, $V_{REF}$. If $V_{IN}$ is greater than the initial output of the ramp
generator, which is applied to the negative terminal of the comparator, begins to rise. Because $V_{IN}$ is greater than the output of the ramp generator, the output of the comparator is high and each clock pulse applied to the AND gate causes the counter at the output to count. Finally, when the output of the ramp generator is equal to $V_{IN}$, the output of the comparator goes low and the output counter is now inhibited. The binary number representing the state of the output counter can now be converted to the desired digital format. The serial A/D converter has the advantage of simplicity of operation. Disadvantages of the single-slope A/D converter are that it is subject to error in the ramp generator and it is unipolar. Another disadvantage of this type of A/D converter is that a long conversion time ($2^N$ clock cycles in the worst case) is required if the input voltage is near the value of $V_{REF}$. A block diagram of a Dual-Slope A/D Converter is shown in Figure 1.3.

![Figure 1.3 Block diagram of a dual-slope A/D converter [3].](image)

The basic advantage of this circuit architecture is the elimination of the dependence of the conversion process on the linearity and accuracy of the ramp generator. Initially, $V_{int}$ is zero, and the input is sampled and held. In this scheme, it is necessary for $V_{in}$ to be positive. The conversion process begins by resetting the positive integrator until the output of the integrator is equal to the threshold, $V_{th}$, of the comparator. Next, $S1$ is closed, and $V_{IN}$ is integrated for $N_{ref}$ number of clock cycles. Figure 1.4 illustrates the conversion process. It is seen that the slope of the voltage at $V_{int}$ is proportional to the amplitude of $V_{IN}$. The voltage, $V_{int}(t)$, during this time is given as
where $T$ is the clock period. At the end of the $N_{\text{ref}}$ counts, the carry output of the counter is applied to switch S2 and causes $-V_{\text{ref}}$ to be applied to the integrator. Now the integrator integrates negatively with the constant slope because $V_{\text{ref}}$ is constant. When $V_{\text{int}}(t)$ becomes less than the value of $V_{\text{th}}$, the counter is stopped, and its binary count can be converted into digital word. This is demonstrated by considering $V_{\text{int}}(t)$ during the time designated as $t_2$ in Figure 1.4. This voltage is given as

$$V_{\text{int}}(t) = V_{\text{int}}(0) + K \int_{0}^{N_{\text{ref}}T} (-V_{\text{ref}}) \, dt$$  \hspace{1cm} (1.3)

![Figure 1.4 Waveforms of the dual-slope A/D converter in Figure 1.3 [3].](image)

However, when $t = N_{\text{out}}T$, then Eq. (1.3) becomes

$$V_{\text{int}}(N_{\text{out}}T) = (KN_{\text{ref}}TV_{\text{IN}} + V_{\text{th}}) - KV_{\text{ref}}N_{\text{out}}T$$  \hspace{1cm} (1.4)

because $V_{\text{int}}(N_{\text{out}}T) = V_{\text{th}}$, then Eq.(1.4) can be solved for $N_{\text{out}}$, giving
\[ N_{\text{out}} = N_{\text{ref}} \left( \frac{V_{\text{in}}}{V_{\text{ref}}} \right) \] (1.5)

It is seen that \( N_{\text{out}} \) will be some fraction of \( N_{\text{ref}} \), where that fraction corresponds to the ratio of \( V_{\text{in}} \) to \( V_{\text{ref}} \).

The output of the serial dual-slope A/D converter (\( N_{\text{out}} \)) is not a function of the threshold of the comparator, the slope of the integrator, or the clock rate. Therefore, it is a very accurate method of conversion. The only disadvantage is that it takes a worst-case time of \( 2(2^N) T \) for a conversion, where \( N \) is the number of the bits of the A/D converter; \( T \) is the clock period. [3]

1.2 Successive Approximation A/D Converters

This class of A/D converters converts an analog input into an \( N \)-bit digital output in \( N \) clock cycles. Also called “bit-at-a-time” converters, their operation principle is based on a binary search, beginning with the most significant bit (MSB). This type of converters includes comparators, Digital-to-Analog converter, and Successive Approximation Register (SAR). Starting with the MSB, the fraction of \( V_{\text{ref}} \) corresponding to each bit is successively added to the fraction corresponding to already determined bits and the sum is compared to the input sample. There exists a trade-off between accuracy and speed (\( N \) comparisons per conversion). Different DAC topologies can be implemented in this type of A/D converters.

![Diagram of Successive Approximation A/D converter](image)

Figure 1.5 Example of a Successive Approximation A/D converter [17].
The function of the digital control logic is to determine the value of each bit in a sequential manner based upon the output of the comparator. The conversion cycle begins by sampling the analog input signal to be converted. Next, the digital control circuit assumes that the MSB is “1” and all other bits are “0”. This digital word is applied the DAC, which generates an analog signal of $0.5V_{ref}$ which is compared to the sampled analog input, $V_{IN}$. If the comparator output is high, then the digital control logic decides that the MSB is equal to “1”. If the comparator output is low, the digital control logic decides the MSB is “0”. This completes the first step in the approximation sequence. At this point, the value of MSB is known. The approximation process continues by applying the digital word to the DAC, with the MSB having its proven value, the next lower bit a “guess” of “1”, and all other remaining bits having a value of “0”. Again, the sampled input is compared to the output of the D/A converter with this digital word applied. If the output of the comparator is high, the second bit is proven to be “1”. If the output of the comparator is low, the second bit is “0”. The process continues in this manner until all bits of the digital word have been decided by the successive approximation process.

Figure 1.6 shows how the successive approximation sequence works in converting the analog output of the D/A converter to the sampled analog input. It is seen that the number of cycles required for the conversion to an N-bit word is N. It is also observed
that as N becomes large, the requirement of the comparator to distinguish between almost identical signals must increase.

A successive approximation A/D converter using an Algorithmic D/A converter is often called an Algorithmic A/D Converter.

![Algorithmic A/D Converter Diagram](image)

Figure 1.7 Pipeline implementation of the algorithmic A/D converter [3].

An algorithmic A/D converter patterned after the algorithmic D/A converter of the preceding stage is shown in Figure 1.7. This N-bit A/D converter consists of N stages and N comparators for determining the signs of the N outputs. Each stage takes its input, multiplies by 2, and adds or subtracts the reference voltage depending on the sign of the previous output. The comparator outputs form an N-bit digital representation of the analog input to the first stage. The algorithmic ADC of Figure 1.7 has the disadvantage that the time to convert a sample is N clock cycles, although one complete conversion can be obtained at each clock cycle. As it is obvious, an algorithmic A/D converter does not need any reference voltage generators, which are usually implemented with capacitor or resistor arrays. Thus, the algorithmic A/D converter is considered to be ratio-independent because the performance does not depend on the ratio accuracy of a capacitor or resistor array. The multiplication by 2 of the first stage must be accurate to within 1 LSB, which is a distinct disadvantage of this configuration of the algorithmic A/D converters. The analog output of the ith stage can be expressed as

\[ V_{O_i} = \left[ 2V_{O_{i-1}} - b_i V_{ref} \right] z^{-1} \]  

(1.6)
where $b_i$ is +1 if the $i$th bit is “1” and −1 if the $i$th bit is “0”.

The iterative version of algorithmic A/D converter given in Figure 1.8 consists of a sample-hold amplifier circuit, a gain-of-2 amplifier, a comparator, and a reference subtraction circuit. The operation of the converter involves first sampling the input signal by connecting switch $S_1$ to $V_{IN}$. Sampled $V_{IN}$ is then applied to the gain-2 amplifier. To extract the digital information from the input signal, the resultant signal, denoted as $V_A$, is less than $V_{ref}$, the corresponding bit is set to “0” and $V_A$ is uncharged. The resultant signal, denoted by $V_B$, is then transferred by means of switch $S_1$ back into the analog loop for another iteration. This process occurs until the desired number of bits have been obtained, whereupon a new sampled value of the input signal will be processed. The digital word is processed in a serial manner with the MSB first. A distinct advantage over the pipeline configuration is that all of the gain-of-2 amplifiers are identical because only one is used in an iterative manner. Sources of error for this A/D converter include low operational amplifier gain; finite input offset voltage in the operational amplifier, charge injection from the MOS switches, and capacitance voltage dependence.

![Figure 1.8 Implementation of the iterative, algorithmic A/D converter [3].](image)

The successive approximation A/D architecture is a very general one, as has been shown. If serial D/A converters are used, the conversion time is increased and the area required is decreased. In general, successive approximation A/D converters can have conversion times that fall within the range of $10^4$ to $10^5$ conversions/second. They are capable of 8 to 12 bits of accuracy. The number of bits can be increased if trimming is permitted.
1.3 Parallel A/D Converters

This type of converters are commonly referred to as parallel or flash converters. In this type of converters the analog input is simultaneously compared with $2^N - 1$ reference voltages where the reference voltages are typically derived from a resistor string.

![Diagram of A/D converter](image)

**Figure 1.9** A 3-bit, parallel (flash) A/D converter [3].

The parallel A/D converter of Figure 1.9 converts the analog signal to a digital word in one clock cycle, which has two phases. So that this type of converters usually defined “word-at-a-time” converter. During the first phase, the analog input voltage is sampled and applied to the comparator inputs. During the second phase, the digital encoding network determines the correct digital output and stores it in a register/buffer. Thus the conversion is limited by how fast this sequence of events can occur. Complexity and power dissipation are problems for larger resolution.

In Figure 1.10, M successive approximation A/D converters are used in parallel to complete the N-bit conversion of one analog signal per clock cycle, often referred as time-interleaved conversion. The sample and hold circuits consecutively sample and apply the input analog signal to their respective A/D converters. N clock cycles later, the A/D converter provides a digital word output. If M = N, then a digital word is output at every cycle. If one examines the chip area for an N-bit A/D converter using the parallel A/D converter architecture (M=1) compared with the time-interleaved
architecture for \( M = N \), the optimum point for area \textit{and} throughput will be found for a value of \( M \) between 1 and \( N \), for realizing the same resolution.

Figure 1.10 A time-interleaved A/D converter array [3].

Combining the parallel approach with a serial approach results in an A/D converter architecture with high speed and reasonable area. This approach is often called a "Pipeline A/D Converter", particularly if the number of series stages is greater than two. If the number of the series stages is exactly two then the topology is called "Series-Parallel" or often referred to as "Two-Step Flash" converters.

Figure 1.11 Block representation of two-step flash A/D converter architecture [23].
Two-step flash converters are used successively to exchange speed for reduction in complexity and power. The topology can be pipelined. Overlapping LSB of “coarse” stage and MSB of “fine” stage eases constraints on the A/D converter in the “coarse” (first) stage. Only DAC and subtractor circuits need (N+M-1) bit accuracy in this topology.

Two-step architecture described in Figure 1.11 can be generalized to multiple stages, where each stage finds a single bit. Specifically, the first stage finds the most significant bit, $b_1$; the second stage finds the next bit $b_2$, and so on. Unfortunately, a straightforward implementation of this approach would be too slow, since the final bit would not be available until residual errors ripple through the entire converter. A better approach is to also incorporate pipelining such that once the first stage completes its work, it does not sit idle while the remaining lower bits are found, but immediately starts to work on the next input sampled. A block diagram of a two-stage pipelined A/D converter is given in Figure 1.12. Using a pipeline architecture allows the designer to make trade-offs between area and conversion time. This topology is attractive for low power, high-speed data conversion applications, such as video and imaging.

![Diagram showing two stages of pipelined A/D converter](image)

Figure 1.12 Two-stages Pipelined A/D converter configuration [3].

In Figure 1.12 a pipelined A/D converter using two M-bit parallel A/D converters is shown. The method first converts the M MSBs and then converts the M LSBs. Consequently only $2^M - 2$ comparators are required to convert a 2M-bit digital word.
For the configuration given in Figure 1.12, the analog input is applied to the left-hand string of $2^M-1$ comparators during the first clock phase and the M MSBs are decoded during second clock phase. During the third clock phase, the M MSBs are converted to an analog equivalent, which is subtracted from $V_{\text{ref}}$ multiplied by a gain of $2^M$, and applied to the right-hand string of $2^M-1$ comparators. Finally, during the fourth clock phase, the M LSBs are encoded. Thus, if the clock has two phases, then in two clock cycles a 2M-bit digital word will be converted.

A/D converters including self-calibrating, pipelined, oversampled, subranging and delta-sigma converters are classified as high performance A/D converters. As a brief explanation, in subranging A/D converter, the conversion is done in several cycles. In each successive cycle the gain of the residue amplifier is increased, until the full scale of the amplified residue voltage is reached. In this manner, errors can be corrected and removed on each successive cycle.

Oversampled A/D converters offer a means of exchanging resolution in time for resolution in amplitude in order to circumvent the need for complex precision analog circuits. This architecture includes a clocked feedback loop, which produces a coarse estimate that oscillates about the true value of the input, and a digital filter, which averages this coarse estimate to obtain a finer approximation. This approximation is more accurate to more bits at a lower sampling rate. If the resolution of digital estimator N is equal to “1” than the oversampling converter becomes a “Delta-Sigma A/D Converter”. One advantage of Delta-sigma A/D, oversampling converters is that because they obtain resolution by linearly interpolating between two-states, they do not require an array of precision binary scaling elements for the D/A converter. This means that non-linearity errors will not exist. The output of the $\Delta\Sigma$ modulator is applied to a low-pass digital filter whose function is to operate on the 1-bit signal to remove frequencies and quantization noise above the desired signal bandwidth. The output of the filter is a multi-bit digital representation at a lower sampling rate. [17]

To review the current state-of-the-art of ADC topologies, an extensive literature survey was done covering past twelve years. A/D converters published are classified according to their resolution, speed, linearity, power consumption, area, topology and the application it is used in. Results of this work can be seen in Appendix A.

From all these tables, typical applications that require high-speed A/D converters can be distinguished with the desired resolution information given below:
- NTSC/PAL Decoders 8bit, 14-17MS/sec
- HDTV A/D Converters 8-10b, 50-75MS/sec
- CATV channel modems 8-12b, 10-15MS/sec
- ADSL/HDSL Transceivers 12-16b, 3MS/sec
- CDDI Transceivers, VG 8-10b, 30-60MS/sec
- Mag Storage Read Channels 6-8b, 75-150MS/sec
- High-Performance Imagers 12b, 75MS/sec
- Supercollider Data Analyzers 12-16b, 60MS/sec

Table 1.1

![Graph](image)

Figure 1.13 Qualitative comparison of ADC techniques.

As can be seen from Figure 1.13, for fastest applications a Flash or a Pipelined A/D Converter is needed. In the following chapter, proposed design specifications and topology will be examined in detail, giving the reasons of the design decisions made in this work.
2. PERFORMANCE MEASURES OF ANALOG-TO-DIGITAL CONVERTERS

In this chapter, we concentrate on specific performance measures and metrics that are commonly used to specify and to quantify the operational characteristics of ADCs. Many of the performance metrics discussed here will be used in the design phase.

2.1 Quantization Error

Quantization error \( (V_0) \) is the difference in magnitude between analog input and the resulting digital code for the entire input range of the converter.

This phenomenon is an unavoidable result of the fact that every A/D (or D/A) converter must operate with finite number of quantization levels to represent the original input signal. Figure 2.1 shows the DC input-output characteristic of an "ideal" 3-bit ADC with 8 quantization levels, and the corresponding quantization error.

A number of error/performance criteria have been developed to quantify this error. Note that the majority of the measures are defined on the DC input-output transfer characteristics.
Figure 2.1 Input-output characteristic of an ideal 3-bit A/D converter and its quantization error [12].

2.2 Quantization Noise

Assume that the input signal is varying rapidly such that the quantization error signal, $V_Q$, is a random variable uniformly distributed between $\pm \frac{V_{LSB}}{2}$. The probability density function for such an error signal will be a constant value. The average value of the quantization error is found to be zero "0"; in a similar fashion, the rms value of the quantization error is given as $\frac{V_{LSB}}{\sqrt{12}}$. Recalling that the size of $V_{LSB}$ is halved for each bit and assuming $V_{REF}$ remains constant, we see that the noise power decreases by 6 dB for each additional bit in the A/D converter. Thus, given an input signal waveform, a formula can be derived giving the best possible signal-to-noise ratio (SNR) for a given number of bits in an ideal ADC. [2]

$$SNR = 20 \log \left( \frac{V_{rms}}{V_Q(rms)} \right) = 20 \log \left( \frac{V_{REF} / \sqrt{12}}{V_{LSB} / \sqrt{12}} \right) dB$$

$$SNR = 20 \log \left( 2^N \right) = 6.02N \ dB$$

17
Alternatively, a more common SNR formula is to assume $V_{in}$ as a sinusoidal waveform between 0 and $V_{REF}$. Thus, the ac power of the sinusoidal wave is $\frac{V_{REF}}{2\sqrt{2}}$, which results in Eq. 2.2.

2.3 Dynamic Range

The dynamic range of a converter is usually specified as the ratio of the rms (root mean square) value of the maximum amplitude input sinusoidal signal to the rms of output noise plus the distortion measured when the same sinusoid is present at the output [2]. The rms output noise plus distortion is obtained by first eliminating the sinusoid from the measured output. To determine this component for an A/D converter, the output can be converted by FFT and the fundamental of the output signal can be eliminated, or a least-mean-squared fit can be used to find the amplitude and phase of sinusoid at the input signal’s frequency and then subtracting the best-fit sinusoid from the output signal [2]. The dynamic range is also defined as the ratio of the largest input that can be converted to the smallest step size of the converter [12]. For example:

$\text{Vin}(0.4V)$, resolution is 10 bits $\Rightarrow$ quantization step size $= (4-0) / 2^{10} = 3.9062 \text{ mV}$

$\Rightarrow$ dynamic range of this converter can be found from $\text{Vin}$ $\Rightarrow 4V / 3.9062\text{mV} = 1024$

$\Rightarrow$ this number can also be expressed in decibels

$\Rightarrow 20\log(1024) = 60 \text{ dB}$

Dynamic range can also be expressed as an effective number of bits using the Eq. 2.2.

$$SNR = 20\log\left[\frac{V_{in}(\text{rms})}{V_{O}(\text{rms})}\right]$$

$$SNR = 20\log\left[\frac{V_{\text{ref}}}{2\sqrt{2}}\right]$$

$$SNR = 20\log\left(\frac{\sqrt{2/3}2^N}{\sqrt{12}}\right)$$

$$SNR = 20\log\left(\frac{\sqrt{2/3}2^N}{\sqrt{12}}\right)$$

$$SNR = 6.02N + 1.76\text{dB}$$
where the non-integer number \( N \) is called the effective number of bits (c.f. Eq. 2.3).

Finally, it should be mentioned that the distortion level (or nonlinearity performance) of many converters remains at a fixed level and is not a function of the input signal level. Thus, as the input signal level is decreased, the signal-to-distortion ratio decreases. This behavior occurs because the distortion level is often determined by component matching and thus is fixed once the converter realized. However, in some converters, the distortion level decreases as the input signal level is decreased, which is often a desirable property to have.

2.4 Resolution

The resolution of a converter is defined to be the number of distinct analog levels corresponding to the different digital words. Thus, an \( N \)-bit resolution implies that the converter can resolve \( 2^N \) distinct analog levels. Resolution is not necessarily an indication of the accuracy of the converter, but instead it usually refers to the number of digital input or output bits.

2.5 Effective Number of Bits (ENOB)

ENOB of a converter is defined with the equation given in Eq. 2.2.

\[
ENOB = \frac{SNR - 1.76}{6.02} \tag{2.3}
\]

For a perfect 12 bit A/D converter, SNR can be calculated as 72dB from Eq. 2.2, then

\[
ENOB = \frac{72dB - 1.76}{6.02} = 11.68bits \tag{2.4}
\]

2.6 Differential Nonlinearity (DNL)

In an ideal converter, each analog step size is equal to 1LSB(Least Significant Bit). In other words in an A/D, the transition values are precisely 1LSB apart.
Differential nonlinearity (DNL) is the measure of how uniform the transition step sizes are. Each step size is compared to the ideal step size:

\[
DNL = \text{LSB width} - \text{Code width} = 1 - \frac{V(x) - V(x + 1)}{\text{LSB}}
\]  \hspace{1cm} (2.5)

Thus an ideal converter has its maximum DNL of “1” for all digital values. If DNL is less than 1LSB then there will not be any missing codes. Whereas if DNL is less than 0.5LSB; the converter will be called “monotonic”. The DNL is illustrated for a 4-bit ADC in Figure 2.2.

![Figure 2.2 Illustration of DNL [12].](image)

**2.7 Integral Nonlinearity (INL)**

The integral nonlinearity (INL) error is defined to be the deviation of the code midpoints from a straight line, or from their ideal location. Note that there exist different conventions concerning the definition of this “ideal line”. Consequently, each convention will result in a slightly different INL value.
1. Drawing a straight line between the first and last code endpoints of the converter’s transfer response.

2. Drawing the best-fit line using all measured code midpoints, such that the maximum difference (or perhaps the mean squared error) is minimized.

3. Drawing a straight line between the ideal location of the first and last code midpoints and using the ideal LSB to calculate the other midpoint locations.

\[ \text{INL} = M(x) - (V_z - 0.5 \text{LSB}_{-} \text{DUT} + x \text{LSB}_{-} \text{DUT}) \]  \hspace{1cm} (2.6)

where \( M(x) \) is the midpoint of code \( x \), \( V_z \) is the midpoint of the first code and DUT is the abbreviation for device under test in Eq. 2.6. The definition of INL is illustrated in Figure 2.3.

Note that a differential error is a particular step size at any specific location in the converter transfer function. Integral error is equivalent to the integration (summation) of the errors along the converters transfer function. (cf. Figure 2.4)

![Graph showing INL for a 3-bit A/D converter](image)

Figure 2.3 Illustration of INL for a 3-bit A/D converter [12].
2.8 Absolute Accuracy

The magnitude of the deviation from the actual to the ideal transfer function of an ADC is called the absolute accuracy of the converter. The absolute accuracy includes the offset, gain and linearity errors (Figure 2.5).

Accuracy can be expressed as a percentage error of full-scale value, as the effective number of bits, or as a fraction of an LSB. For example; a 12-bit accuracy implies that that converter’s error is less than the full-scale value divided by $2^{12}$.

The term relative accuracy is sometimes used and is defined to be the accuracy after the offset and gain errors have been removed. It is also referred to as the maximum integral nonlinearity error (described in section 2.6) and we will refer to it as such.
Figure 2.5 Absolute accuracy is the summation of other error sources [12].

2.9 Gain error

Gain is equal to slope of the converter's transfer function. The ideal slope of the transfer function is found by $V_{\text{FULLSCALE}} / (2^n - 1)$. The gain error is defined to be the difference (at the full-scale value) between the ideal and actual curves when the offset error has been reduced to zero in units of LSBs in Eq. 2.7. Gain error can also be specified as the deviation of the highest transition level on the ADC transfer function from its ideal location.

$$E_{\text{gain(A/D)}} = \left[ \frac{V_{\text{FULLSCALE}}}{V_{\text{LSB}}} \right] - (2^N - 2) \quad (2.7)$$
Figure 2.6 Illustration of gain error [12].

2.10 Offset Error

Identifies the deviation of the lowest transition level from its ideal location.

\[ V_{off} = V_Z - (0.5LSB) \]  \hspace{1cm} (2.8)

where \( V_Z \) is the first transition level voltage. The offset error between an actual and an ideal ADC transfer function is illustrated in Figure 2.7.

2.11 Transition Level

Each digital output code has associated with its two bounding transition levels. When the magnitude of the input lies between these two transition levels the code is generated and is the digital output. Ideally these transition levels are infinitely narrow thresholds; however, because of noise and other error sources the transition level will have a noise band with it. In this transition band there is a varying probability of the converter generating one code or the other. The point where there is a 50% chance of
converting one code or the other code is defined as the transition level illustrated in Figure 2.8.

Figure 2.7 Illustration of offset error [12].

Figure 2.8 Illustration of transition level [12].
2.12 Monotonicity

In an ideal ADC, the converted digital output code is always expected to increase as the input signal increases. In other words, the slope of the converter's transfer response curve must always be positive. Thus, a converter is guaranteed to be monotonic, i.e., its transfer curve exhibits monotonically increasing behavior, if the maximum INL is less than 0.5LSB.

![Diagram showing monotonic and nonmonotonic behavior of ADC transfer function](image)

Figure 2.9 A nonmonotonic ADC transfer function [12].

2.13 Missing Code

A converter must be able to correspond all possible digital outputs to an analog input. An A/D converter is guaranteed not to have any missing codes if the maximum DNL error is less than 1LSB or if the maximum INL is less than 0.5LSB.
Figure 2.10 An ADC transfer function with a missing code (100) [12].

2.14 Differential Phase and Gain

Differential phase is the difference in the output phase of an A/D converter when a small high frequency sine-wave signal is superimposed on a low frequency signal at two predescribed amplitudes.

Differential gain is the ratio of the output amplitudes of an A/D converter with this small high frequency sine wave superimposed on the low frequency signal at the two predescribed amplitudes.

2.15 Conversion Time and Sampling Rate

The conversion time is the time taken for the converter to complete a single measurement including acquisition time of the input signal. It is also called the “Latency”, the interval when the analog input is sampled and when the associated digital code is valid at the output of the converter.

On the other hand, the maximum sampling rate is the speed at which samples can be continuously converted and is typically the inverse of the conversion time. Note that, some converters have a large latency between the input and the output due to pipelining
or multiplexing, yet they still maintain a high sampling rate. The relation between sampling rate and conversion time (latency) is illustrated in Figure 2.11.

2.16 Sampling-Time Uncertainty

ADC’s have limited accuracy when their sampling instances are ill defined. To quantify this sampling time uncertainty, also known as “Aperture Jitter”, for sinusoidal waveforms, consider a full-scale signal, $V_{in}$, applied to an N-bit A/D converter with frequency $f_{in}$. Since the slope of $V_{in}$ at the peak of a sinusoidal waveform is small, sampling time uncertainty is less of a problem near the peak values. However, the maximum rate of change for this waveform occurs at the zero crossing and can be found by differentiating $V_{in}$ with respect to time and setting $t=0$. At zero crossing

$$\Delta V \bigg|_{\text{max}} = \pi f_{in} V_{amplitude}$$

(2.9)

If $\Delta t$ represents some sampling-time uncertainty, and if we want to keep $\Delta V$ less than 1LSB, so that

$$\Delta t < \frac{V_{LSB}}{\pi f_{in} V_{ref}} = \frac{1}{2^N \pi f_{in}}$$

(2.10)

Figure 2.11 Illustration of sample period and conversion time.
2.17 Input Bandwidth

Input bandwidth specifies the highest frequency analog signal an ADC can convert and still meet its performance specifications. Usually converters are required to convert input signals with bandwidths up to $\frac{1}{2}$ their sampling rate (Nyquist rate). Input bandwidth is very a dependent quantity on maximum sampling rate.

Maximum sampling rate of a converter is a difficult to define number. In some cases the reduction in dynamic range (S/N ratio) can be used to define the maximum sampling rate. A definition can be given as:

The maximum sampling frequency of the converter for which the dynamic range measured over the Nyquist bandwidth is reduced with 3dB or 0.5 bit.

This definition gives a rough indication about the maximum sampling frequency. Thus, the input bandwidth can roughly be defined as the half of the maximum sampling rate.
3. PIPELINED ANALOG-TO-DIGITAL CONVERTERS

In this chapter, we will examine high-throughput A/D converters that are capable of producing high-resolution output (greater than 10-bits), and specifically concentrate on pipelined converter architectures. To start the discussion, we first summarize the main properties of various ADC architectures in the following, to serve as a means of comparison.

➤ Flash Converters
  * Exponentially increasing hardware complexity with resolution
  * Impractical above 8-bit resolution
  * Large power dissipation and input capacitance.

➤ Two-Step Flash Converters
  * Requires multiple clocks cycles per conversion
  * Hardware increases exponentially with resolution.

➤ Pipelined Converters
  * High degree of concurrency
  * One output sample per clock cycle
  * Approximately linear hardware cost with resolution
  * Same throughput as Flash, with the cost of fast interstage processing
  * Much less hardware than Flash converters
  * Amenable to self-calibration and digital correction.
Parallel Pipelined Converters

- Increase throughput by time-interleaving
- Share resources across multiple channels, keeping area and power reasonable
- Performance is limited by channel offset mismatch, channel gain mismatch, multiphase clock generation resulting jitter and skew.

The two-stage architecture described in Chapter 1 can be generalized to multiple stages, where each stage determines a single bit. Specifically, the first stage determines the most significant bit, $b_1$; the second stage finds the next bit $b_2$, and so on. Unfortunately a straightforward implementation of this approach would be too slow, since the final bit would not be available until residual errors ripple through the entire converter. So, multi-step A/D converters have replaced two-stage architectures, given in Figure 3.1, for higher speed applications.

![Figure 3.1 Typical two-step A/D converter architecture [21].](image)

This topology substitutes speed for reduction in complexity and power, and it can use digital correction to ease the constraints on the coarse A/D converter. Performance limitations of this topology can be listed as follows:

- A front-end sample-hold amplifier is required.

\[
V_{in} = V_A \sin(w_n t)
\]
\[
\frac{dV_{in}}{dt} \bigg|_{\text{max}} = V_A w_n
\]
without a sample-hold (S/H) amplifier, the input is not allowed to change more than 0.5LSB during the time it takes to perform the coarse quantization, D/A conversion, and subtraction. If this time is denoted as $t_{\text{coarse}}$, then

$$
t_{\text{coarse}} \leq \frac{1}{\pi f_m 2^{N+1}}
$$

(3.2)

The second "fine" A/D converter must have a resolution equal to $N$-bits. (Figure 3.2). In order to relax this demanding constraint for the stage-two ADC, residue voltage can be amplified by a factor of $2^M$ before the second A/D conversion step. This allows the second step ADC to have a lower resolution, and still produce the lower-order bits properly. (Figure 3.3)

![Figure 3.2 Multi-Step A/D converter figure of performance illustration [21].](image)
Figure 3.3 Multi-Step A/D converter's figure of performance illustration with internal amplification [21].

Thus, the front-end SHA, D/A converter, and subtractor directly affect overall performance. Conversion speed is set by the time needed to perform multiple operations. Note that there still exists an exponential dependence of circuit area and power dissipation with the desired resolution. Multi-step A/D converter's speed is proportional to the number of stages employed.

Combining series-parallel topologies together with a small number of bits/stage; results in a “Pipelined” topology which is very attractive for low power, high speed data conversion in applications such as video and imaging. A simple pipelined architecture is illustrated in Figure 3.4.

Figure 3.4 A simple Pipelined A/D converter architecture [21].
This topology trades conversion speed for latency by using interstage sample-hold amplifiers. Speed is limited by conversion speed of one stage in this topology. The number of components grows linearly with resolution, and scaling can be employed to minimize power dissipation and circuit area; if interstage amplification is employed.

Performance limitations of the topology and some possible remedies can be listed as follows:

- Pipelined ADC architectures require additional analog processing such as interstage sample-hold amplifier, D/A converter, subtractor and amplification,
- Latency may be a problem in some systems,
- D/A converters nonlinearity and amplifier gain error are the principal contributors to the overall converter's nonlinearity; these can be corrected using techniques such as self-calibration and error averaging.
- A/D nonlinearity and amplifier offset can be compensated by using digital error correction.
Figure 3.6 A pipelined A/D converter architecture model with offset and gain error for both the S/H amplifier and the residue amplifier [21].

3.1 Pipelined Operation

To understand how errors in a pipeline stage affect the converter's overall performance it is necessary to understand the ideal pipeline behavior.

Consider the 3-bit pipeline given in Figure 3.7, based on a 1-bit per-stage topology.

Figure 3.7 A 3-bit (1-bit per stage) pipelined A/D converter [21].

Figure 3.8 Implementation of each stage in Figure 3.7 [21].
The transfer function for the 1-bit pipelined stage is given in Eq. 3.3 and plotted in Figure 3.9.

\[
V_{out} = 2V_{in} - D_n V_{ref} + D_n V_{ref}
\]  
(3.3)

![Figure 3.9 The transfer function of the 1-bit stage shown in Figure 3.8 [21].](image)

For a pipelined A/D converter, the overall transfer characteristic can be generated by starting at the LSB stage (the final stage) and proceeding back to the MSB stage. For the pipeline example given above, the 3-bit A/D has the following transfer function:

![Figure 3.10 Transfer function of 3-bit pipelined A/D converter [21].](image)
To derive the transfer function given in Figure 3.10; first the threshold voltages of the stages’ comparators are found. For ideal comparators, as the analog input to the converter passes through these thresholds the digital output will change by 1LSB. So for stage “n”:

\[ V_s < 0V \implies D_n = 0; \]
\[ V_s > 0V \implies D_n = 1 \quad (3.4) \]

Figure 3.11 Detailed transfer function characteristics [21].

The transfer function stated above; points out an important fact about the pipeline architecture. Each group of stages is itself an A/D converter. This A/D simply quantizes the outputs of the preceding stage. Because both portions of each stage’s transfer characteristics completely span the resolvable input range of the following group of stages, all digital codes of the group of stages are ideally accessed.

In Table 3.1 a brief summary of high speed pipelined ADC performance figures are given for comparison purposes. It can be seen from Figure 3.12 and Figure 3.13, that pipelined converters usually achieve a favorable balance between high resolution (≥ 10 bits), high sampling rate, and “acceptable” silicon area. The price for these advantages, however, is paid in terms of a more complicated signal flow path, additional functions such as interstage DACs, and residue amplifiers. In these figures, FM1 is the ratio of sampling rate to equivalent technology f_t multiplied by 10^3 and FM2 is a power figure of merit normalized to technology f_t. It is given by

\[ FM2 = \frac{2^p (SR)}{PF_t} \quad (3.5) \]
where $P$ is power dissipation, $B$ is number of bits, $S_r$ is sampling rate and $f_e$ is the effective unity current gain frequency of the technology.

Figure 3.12 Comparison of speed figure of merit, between Flash, 2-Step, and Pipeline ADCs
Figure 3.13 Comparison of power figure of merit, between Flash, 2-Step, and Pipeline ADCs.
<table>
<thead>
<tr>
<th>Author</th>
<th>Rate (MS/s)</th>
<th>Resolution (bits)</th>
<th>Technology</th>
<th>Power (W)</th>
<th>Area (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lewis, UCB, ISSCC86</td>
<td>5</td>
<td>9</td>
<td>3uCMOS</td>
<td>0.18</td>
<td>10k</td>
</tr>
<tr>
<td>Song, U.Ill, ISSCC88</td>
<td>1</td>
<td>12</td>
<td>1.5uCMOS</td>
<td>0.4</td>
<td>7.8k</td>
</tr>
<tr>
<td>Robertson, AD, ISSCC90</td>
<td>20</td>
<td>10b</td>
<td>BICMOS</td>
<td>1.0</td>
<td>85k</td>
</tr>
<tr>
<td>Lin, UCB, VLSI90</td>
<td>2.5</td>
<td>13b</td>
<td>3uCMOS</td>
<td>0.1</td>
<td>40k</td>
</tr>
<tr>
<td>Lewis, ATT, CICC91</td>
<td>20</td>
<td>10b</td>
<td>1uCMOS</td>
<td>0.3</td>
<td>12k</td>
</tr>
<tr>
<td>Corcora, HP, ISSCC92</td>
<td>2</td>
<td>12b</td>
<td>7Gbps</td>
<td>3.5</td>
<td>26k</td>
</tr>
<tr>
<td>Karanico, MIT, ISSCC93</td>
<td>1</td>
<td>15b</td>
<td>4G, 2.4u BiCMOS</td>
<td>1.8</td>
<td>100k</td>
</tr>
<tr>
<td>Kusumoto, Mats, ISSCC93</td>
<td>20</td>
<td>10b</td>
<td>0.8uCMOS</td>
<td>0.03</td>
<td>10k</td>
</tr>
<tr>
<td>Sone, Nee, ISSCC93</td>
<td>100</td>
<td>10b</td>
<td>0.8 BiCMOS</td>
<td>0.95</td>
<td>32k</td>
</tr>
<tr>
<td>Colleran, UCLA, ISSCC93</td>
<td>100</td>
<td>10b</td>
<td>12Gbps</td>
<td>0.8</td>
<td>30k</td>
</tr>
<tr>
<td>Conroy, VLSI92</td>
<td>85</td>
<td>8b</td>
<td>1.2uCMOS</td>
<td>0.8</td>
<td>35k</td>
</tr>
</tbody>
</table>

Table 3.1 Pipelined A/D converter performance summary.
3.2 Circuit Implementation of a Pipeline Stage

![Diagram of pipeline stage](image)

Figure 3.14 Implementation of i-th stage of a pipelined converter. [21]

A pipelined stage given in Figure 3.14, consists of a sample-hold amplifier in order to achieve analog pipelining, an A/D converter (usually flash A/D converters are preferred because of speed considerations), a D/A converter (current based or multiplying), a residue amplifier which will generate the analog input signal for the next pipelined stage, also called interstage amplifier, flip-flops for digital pipelining and fast adders to assemble the final digital output. A flash ADC generally consists of a resistor chain to generate the reference voltages, which is followed by an array of voltage comparators. Outputs of these voltage comparators are directly fed into the following D/A converter to establish digital-to-analog conversion for the rest of the operations. This converted analog signal, usually called the "residue" voltage, is applied to the interstage amplifier. Thus, an amplified residue voltage is obtained, which replaces the analog input signal for the following pipeline stage.

The most common error sources for these circuits are:

* Capacitor mismatch for Multiplying D/A converter
* Sampling switch charge injection
* Comparator offset
* Op-Amp gain error
* Resistor mismatch
* Offset of sample-hold amplifier and interstage amplifier
The general effect of these sources of error is to cause output voltages of a stage to not exactly match the resolvable input range of the remaining pipeline stages. Capacitor mismatch, op-amp gain error and D/A nonlinearity directly affect the converter's overall linearity. Calibration techniques or trimming must be employed if high linearity is desired. Comparator offset, which causes nonlinearity in the interstage A/D converter, and switch charge injection can be corrected by using digital correction. The basic idea of digital correction is to provide overlap between the quantization ranges of adjacent stages by using extra comparators. Using the proper digital encoding; a linear transfer characteristic can be obtained.

3. 3 MATLAB Simulation Results

In this section, we study the influence of various design parameters on the performance of a 4-bit ADC, which may form the main building blocks of a pipelined converter. MATLAB is used to model a four-bit flash Analog-to-Digital converter consisting of a resistor chain and an array of voltage comparators. The inaccuracy of resistor chain, comparator offset, supply voltage variation and input voltage range, which are the most important and most effective parameters on converter's performance, are modeled in order to see the effects on DNL and INL. Each of the parameters were set to vary one-by-one and also all together. Possible inaccuracies of the resistor chain that is used to obtain the reference voltages was modeled by a variation of the individual reference voltages. While modeling these parameters, process variation information and preliminary specifications of the Analog-to-Digital converter were taken into account. In the presence of this knowledge, the range of variation of the four parameters was set as follows.
<table>
<thead>
<tr>
<th>PARAMETER (Individual)</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>0.2 V</td>
<td>1.8 V</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1.71 V</td>
<td>1.89 V</td>
</tr>
<tr>
<td>Comparator Offset</td>
<td>± 1 mV</td>
<td>± 160 mV</td>
</tr>
<tr>
<td>Reference Voltage Variation</td>
<td>-7 mV</td>
<td>7 mV</td>
</tr>
</tbody>
</table>

Table 3.2 Parameter limit values applied to MATLAB code.

MATLAB simulations were run on these parameters for one thousand different points per simulation. In each simulation only one of the parameters changed while others were set to their nominal value. In order to see what effects will occur because of this specified parameter variation. From the results obtained it was decided to do mixed simulations (all four parameters vary independently from each other in one simulation run) within a specified range for all parameters. These parameter set is given below.

<table>
<thead>
<tr>
<th>PARAMETER (Mixed)</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Range</td>
<td>0.8 V</td>
<td>1.6 V</td>
</tr>
<tr>
<td>Supply Voltage</td>
<td>1.71 V</td>
<td>1.89 V</td>
</tr>
<tr>
<td>Comparator Offset</td>
<td>± 5 mV</td>
<td>± 20 mV</td>
</tr>
<tr>
<td>Reference Voltage Variation</td>
<td>-7 mV</td>
<td>7 mV</td>
</tr>
</tbody>
</table>

Table 3.3 Parameter limit values that will be used in the input stimuli for combined parameter set MATLAB simulations.

It can be seen from the DNL and INL envelope graphs that each parameter has different influence on the performance of the 4-bit A/D converter. A deeper investigation of the graphs shows the following results:
<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>DNL (maximum)</th>
<th>INL (maximum)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage Variation</td>
<td>± 0.01 LSB</td>
<td>± 0.01 LSB</td>
</tr>
<tr>
<td>Reference Voltage Variation</td>
<td>± 0.52 LSB</td>
<td>± 0.01 LSB</td>
</tr>
<tr>
<td>Comparator Offset</td>
<td>0.56 LSB</td>
<td>0.08 LSB</td>
</tr>
<tr>
<td>Supply Voltage Variation</td>
<td>-0.6 LSB</td>
<td>0.01 LSB</td>
</tr>
<tr>
<td>MIXED</td>
<td>4 LSB</td>
<td>0.18 LSB</td>
</tr>
</tbody>
</table>

Table 3.4 Maximum and minimum values obtained for INL-DNL characteristic for each parameter.

DNL and INL values for input voltage variation does not change too much because reference voltages for fifteen levels of comparators are determined due to the input voltage level in order to be able to do comparison with all comparators.

A maximum tolerable DNL value -which is 0.52 LSB - occurs for a +/- 7 mV resistor voltage variation. Also it could be seen that the integral nonlinearity is not affected too much with changing the reference voltages obtained with a resistor voltage divider.

Comparator offset of 50 mV creates a DNL equal to 0.56 LSB, while an INL of 0.08 LSB is observed for 160 mV comparator offset. It could be dictated that comparator offset must not exceed 50 mV.

A ± 5% supply voltage variation creates ± 0.6 LSB DNL and the integral nonlinearity is not affected too much with supply voltage variation.

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>1 V</td>
</tr>
<tr>
<td>Resistor Voltage Variation</td>
<td>± 7 mV</td>
</tr>
<tr>
<td>Comparator Offset</td>
<td>± 10 mV</td>
</tr>
<tr>
<td>Supply Voltage Variation</td>
<td>± % 5</td>
</tr>
</tbody>
</table>

Table 3.5 Maximum tolerable input parameter set.

As a result analog input voltage range should not be less than 0.8Vpp; 7mV is the upper limit for resistor voltage variation; similarly 20mV is the critical value for comparator offset and 1.89V is the maximum tolerable supply voltage in order not to
exceed 0.5LSB Integral-differential nonlinearity ranges. All possible INL-DNL envelopes are given above for all parameters individually and for also combined set of input parameters. It was decided to use the limit values shown in Table 3.5 as a general guideline for the transistor level design of the 4-bit flash ADC components.

Figure 3.15 INL envelope obtained for different input voltage ranges.
Figure 3.16 DNL envelope obtained for different input voltage ranges.

Figure 3.17 INL envelope obtained for different resistor voltage variations.
Figure 3.18 DNL envelope obtained for different resistor voltage variations.

Figure 3.19 INL envelope obtained for different comparator offsets.
Figure 3.20 DNL envelope obtained for different comparator offsets.

Figure 3.21 INL envelope obtained for different supply voltage variations.
Figure 3.22 DNL envelope obtained for different supply voltage variations.

Figure 3.23 INL envelope obtained for combined parameter set simulations.
Figure 3.24 DNL envelope obtained for combined parameter set simulations.
4. ARCHITECTURE COMPONENTS: VOLTAGE COMPARATOR DESIGN

4.1 Pipelined ADC Architecture Overview

Based on the observations outlined in Chapter 3, we propose a Pipelined A/D converter that is formed by four stages of 4-bit Flash A/D converters, followed by the corresponding D/A converters, subtraction circuits and residue amplifiers (Fig. 4.1). Brief design specifications of the proposed Analog-to-Digital converter are given in Table 4.1.

- **Architecture**: Pipelined (4 stages)
- **Sampling Rate**: 200 MS/s
- **Resolution**: 12 bits (4-bits per stage)
- **Technology**: 0.18 µm CMOS, 1.8V technology.
- **Power dissipation**: <100mW
- **Die size**: <10-15 mm²

Table 4.1 Design specifications of proposed pipelined A/D converter.
Figure 4.1 Simplified block diagram of the proposed A/D converter architecture.

Figure 4.2 Detailed circuit architecture for one of the four proposed pipelined stages.
The detailed circuit architecture of one of the proposed pipeline stages is shown in Fig. 4.2. The 4-bit flash ADC consists of a resistor chain to generate the reference voltages, followed by an array of voltage comparators. The outputs of the comparators are fed directly into a capacitive MDAC (Multiplying DAC) that simultaneously performs the subtraction of the re-constructed digital output from the original analog signal, as well as the amplification of the residue signal voltage for further processing by the next pipeline stage. Note that single-ended signals (as opposed to differential) are used in the entire circuit architecture. In the following, we will investigate the design of the main components of this architecture, starting with the voltage comparator.

4.2 Voltage Comparators: Basic Concepts

The most important component in flash A/D converters is the voltage comparator. The comparator is a circuit that compares an analog signal with another analog signal, and outputs a binary signal based upon the comparison. What is meant here by an analog signal is one that can have any value of a continuous range of amplitude values at a given point in time. In the most strict sense a binary signal can have only one of the two given values at any point in time, but this concept of a binary signal is too ideal for real world situations, where there is a transition region between the two binary states.

The realization of high-speed, high-precision voltage comparators is one of the key issues in the design of data conversion systems. Traditionally, the main trade-off is between speed and accuracy, where device mismatch effects tend to limit the achievable accuracy in high-speed configurations. Silicon area and power dissipation are also among the main concerns. In addition, the complexity of the clocking schemes used in high-speed comparators can easily be one of the limiting factors in system design.

The widespread dominance of low-voltage digital CMOS process in mixed-signal IC design implies that high-performance analog circuit blocks such as voltage comparators must be designed with the restriction of a single, relatively low power supply voltage. Also, on-chip noise considerations introduce the need to utilize an increasing percentage of the available power supply range as the input dynamic range. Consequently, the design of high-speed low voltage comparators becomes a serious challenge.
4.2.1 Model of a Voltage Comparator

Figure 4.3 shows the circuit symbol for a comparator. This symbol is similar to that of an operational amplifier, because a comparator has many of the same characteristics as a high-gain amplifier. A comparator was defined in the introduction as a circuit that has a comparison of two analog inputs. This is illustrated in Figure 4.4. As shown in this figure the output of the comparator is high ($V_{OH}$) when the difference between the non-inverting and inverting inputs is positive and low ($V_{OL}$) when this difference is negative.

![Comparator Circuit Symbol](image)

Figure 4.3 Circuit symbol for a comparator [3].

![Zero-order Transfer Curve](image)

Figure 4.4 Zero-order transfer curve of a comparator [3].

Even though this type of behavior is impossible in a real-world situation, it can be modeled with ideal circuit elements with mathematical descriptions. One such circuit model is shown in Figure 4.5. It comprises a non-linear voltage-controlled-voltage source (VCVS) whose characteristics are described by the mathematical formulation given on the figure.
Figure 4.5 Zero-order model for a comparator [3].

The ideal aspect of this model is the way in which the output makes a transition between $V_{\text{OL}}$ and $V_{\text{OH}}$. The output changes states for an input change of $\Delta V$, where $\Delta V$ approaches to zero. This implies a gain of infinity, as shown below

$$Gain = A_v = \lim_{\Delta V \to 0} \frac{V_{\text{OH}} - V_{\text{OL}}}{\Delta V}$$

(4.1)

Figure 4.6 shows the DC transfer curve of a first-order model that is an approximation to a realizable comparator circuit. The difference between this model and the previous one is the gain, which can be expressed as

$$A_v = \frac{V_{\text{OH}} - V_{\text{OL}}}{V_{\text{IH}} - V_{\text{IL}}}$$

(4.2)

where $V_{\text{IH}}$ and $V_{\text{IL}}$ represent the input-voltage difference $v_p - v_N$ needed to just saturate the output at its upper and lower limit respectively.
Gain is a very important characteristic describing comparator operation, for it defines the minimum amount of input charge necessary to make the output swing between the two binary states. The voltages $V_{OH}$ and $V_{OL}$ must be adequate to meet the $V_{IH}$ and $V_{IL}$ requirements of the following digital state.

The transfer curve of Figure 4.6 is modeled by the circuit of Figure 4.7. This model looks similar to the one for zero-order model, the only difference being the functions $f_1$ and $f_0$. The second non-ideal effect seen in comparator circuits is input-offset voltage. In Figure 4.4, the output changes as the input crosses zero. If the output does not change until the input difference reaches a value $+V_{OS}$, then this difference would be defined as the offset voltage (Figure 4.8). The corresponding equivalent circuit model of a comparator with input offset is shown in Figure 4.9 [3].
Figure 4.8 First-order transfer curve of a comparator including offset [3].

Figure 4.9 First-order model of a comparator including offset. The ± sign of the offset voltage accounts for the fact that $V_{OS}$ is unknown in polarity [3].

Up to this point in our discussion we have considered only the DC model for a comparator. This model includes the parameters of gain, amplitude saturation and offset voltage. The comparator must also be modeled in the time domain. Figure 4.4 and Figure 4.6 show that the output of the comparator changes from one state to another for a given amount of differential output. The point of question is, how long it takes for the comparator to respond to the given differential input. The characteristic delay between input excitation and output transition is the time response of the comparator. Figure 4.10
illustrates the response of a comparator to an input as a function of time. Notice that there is a delay between the input excitation and the output response.

![Diagram of comparator response](image)

Figure 4.10 Time domain response of a non-inverting first-order comparator [3].

This time difference is called the propagation delay of the comparator. It’s a very important parameter since it’s often the speed limitation in the conversion rate of an A/D converter. The propagation delay in comparators usually varies as a function of the amplitude of the input. A larger input will result in a smaller delay time. There is an upper limit at which a further increase in the input voltage will no longer affect the delay.

Perhaps the major limitation on the resolution of comparators is due to charge injection, also commonly called clock feed through. This error is due to unwanted charges being injected into the circuit when transistors turn-off. When MOS switches are on, they operate in the triode region and have zero volts between their drain and source terminals. When MOS switches turn-off, charge errors occur by two mechanisms. The first is due to the channel charge, which must flow out from the channel region of the transistor to the drain and the source junctions. The channel charge of a transistor that has zero $V_{DS}$ is given by,

$$Q_{CH} = W L C_{ox} V_{eff} = W L C_{ox} (V_{GS} - V_I)$$  \hspace{1cm} (4.3)
This charge often dominates the second charge (typically smaller, unless $V_{	ext{off}}$ is very small) which is due to the overlap capacitance between the gate and the junctions.

4.2.2 Examples of CMOS Comparator Circuits

This section describes a number of high-speed comparators that are preferred in flash ADC circuit structures.

One of the simplest circuits available in CMOS technology that can function as a comparator is the current-sink inverter given in Figure 4.11.

![Figure 4.11 Current-sink inverter functioning as a comparator [3].](image)

The transfer curve of this inverter is shown in Figure 4.12. The input voltage range of the comparator is approximately determined by the gain of the comparator. The larger
the gain, the smaller the input-voltage drive requirements. The major drawback of this circuit is not gain, however, but the fact that the trip point is dependent upon power supply. In addition, there is a limited range at which the trip point can be placed, while still maintaining adequate gain. All these problems can be solved by using a differential input scheme.

![Diagram of a differential voltage comparator schematic](image)

Figure 4.13 Differential voltage comparator schematic [3].

![DC transfer curve of a differential voltage comparator](image)

Figure 4.14 DC transfer curve of a differential voltage comparator [3].
Figure 4.13 shows the differential amplifier stage with n-channel input devices and a single ended output stage. The key attribute of this circuit is its ability to amplify the difference between the inverting and non-inverting inputs. As a result the trip-point of a comparator can be made independent of process and supply variation to the first order. The major drawback of using the differential stage alone as a comparator is the limited output range, which would probably not be useful for driving digital circuitry. The limit of the output swing range is given in Eq. 4.4. Also the limited gain of this single stage is one of the problems.

\[
V_{CL} = V_P - V_{TM1} \\
\frac{V_{OH}}{V_{ODH}} = \frac{I_s}{K_3 \left( \frac{W_3}{L_3} \right)}
\]  

(4.4)

Thus far, two circuit techniques to implement the comparator function have been presented. However, neither of the presented circuits performs the comparator function satisfactorily by itself. But, although these two circuits do not perform well alone; they can have satisfactory performance if they are combined. Figure 4.15 shows the circuit diagram of a two-stage comparator.

![Two-stage voltage comparator](image_url)

Figure 4.15 Two-stage voltage comparator [3].
The poor gain of the differential stage is augmented by the gain of the inverting stage. The output of the differential stage that lies closest to $V_{DD}$ is in the vicinity of the trip-point of the inverting stage that follows. Therefore the limited output range, which is a problem for the differential stage by itself, now becomes a good feature in the combination shown. In Figure 4.15 the total offset seen at the input of the comparator is due to the second-stage offset rectified to the input and added to the offset in the first-stage. There also exists some error in the output resulting from the current mismatches. This error is then reflected back to the input as a systematic offset.

Often a comparator is placed in a very noisy environment in which it must detect signal transitions at the threshold point. Specifically, hysteresis may be needed in the comparator. Hysteresis is the quality of the comparator in which the input threshold changes as a function of the input (or output) level. In particular, when the input passes the threshold, the output changes and the input threshold is subsequently reduced so that the input must return beyond the previous threshold before the comparator's output changes state again.

![Comparator hysteresis curve](image)

Figure 4.16 Comparator hysteresis curve [3].

The output uncertainty of the comparator can be minimized by adding hysteresis equal to or greater than the amount of the largest expected noise amplitude.
Figure 4.17 Comparator with hysteresis applied to the input differential stage only [3].

Figure 4.18 (a) Comparator response to a noisy input. (b) Comparator response to noisy input when hysteresis is added [3].

In this circuit there are two paths of feedback. The first is current-series feedback through the common source node of transistors M1 and M2. This feedback path is
negative. The second path is the voltage-shunt feedback through the gate-drain connections of transistors M10 and M11. This path of feedback is positive. If the positive feedback factor is less than the negative feedback factor, then the overall feedback will be negative and no hysteresis will result. If the positive feedback factor becomes greater, the overall feedback will be positive, which will give rise to hysteresis in the voltage transfer curve. As long as the ratio $\beta_{10} / \beta_3$ is less than one, there is no hysteresis in the transfer function. When this ratio is greater than one, hysteresis will result [3].

Input-offset voltage can be a particularly difficult problem in comparator design. Offset cancellation techniques are available in MOS technology because of the nearly infinite input resistance of MOS transistors. This characteristic allows long-term storage of voltages on the transistor’s gate. As a result, offset voltages can be measured, stored on capacitors, and summed with the input so as to cancel the offset.

![Circuit diagram](image)

**Figure 4.19** (a) Circuit implementation of an auto-zeroed comparator. (b) Comparator during $\phi_1$ auto-zero state. (c) Comparator during $\phi_2$ state [3].
One possible implementation of an auto-zeroed comparator is shown in Figure 4.19. In order for this circuit to work properly, it is necessary that the comparator be stable in the unity-gain configuration. NMOS switches were drawn instead of CMOS transmission gates for the sake of simplicity. It is also very important to use non-overlapping clocks to drive the switches so that any given switch turns-off before another turns-on. Auto-zero techniques can be very effective in removing a large amount of comparator's input offset, but the offset cancellation is not perfect. Charge injection resulting from clock feed trough can by itself introduce an offset.

The literature on integrated circuit technology has many examples of latched comparators, such as the example shown in Figure 4.20. This comparator has the positive feedback of the second stage always enabled. In track mode, when two diode-connected transistors of the gain stage are enabled, the gain around the positive feedback loop is less than one, and the circuit is stable. The combination of the diode-connected transistors of the gain stage and the transistors of the positive feedback loop acts as a moderately large impedance and gives gain from the preamplifier stage to the track-and-latch stage. The diode-connected loads of the preamplifier stage give a limited amount of gain in order to maximize speed, while still buffering the kickback from the input circuitry.

Figure 4.20  A two-stage comparator that has a preamplifier and a positive-feedback track-and-latch stage [2].
A second comparator shown in Figure 4.21, also uses diode-connected loads to keep all nodes at relatively low impedance (similar to current-mode circuit design techniques), thereby keeping all node time constants small and resulting in fast operation. This design also uses precharging to eliminate any memory from the previous decision. For example, the positive-feedback stage is precharged low, whereas the digital-restoration stage is precharged high, somewhat similar to what is done in Domino CMOS Logic.

![Figure 4.21 A two-stage comparator [2].](image)

A third comparator is shown in Figure 4.22, with appropriate wave forms given in Figure 4.23. This design eliminates any input-offset voltages from both the first and second stages by using capacitive coupling. It also has common-mode feedback circuitry for the first preamplifier stage, which allows for input signals that have large common-mode signals.
Figure 4.22 A two-stage comparator with capacitive coupling to eliminate input-offset voltage and clock-feedthrough errors along with positive feedback for fast operation [2].

Figure 4.23 The clock waveforms required by the comparator in Figure 4.22 [2].

With a firm understanding of the basic operational characteristics and the design requirements of voltage comparators, we search for high-speed, high-gain, differential out, low power and resetable comparator architectures with low input offset. Some examples of the state-of-art voltage comparators will be given in the following section.
4.3. Examples of State-of-the-Art Voltage Comparators

Figure 4.24 A fully differential comparator with two nonoverlapping clocks by Lewis and Hurst [34].

The voltage comparator given in Figure 4.24 is a fully differential high-speed comparator. During PH1, +VIN and -VIN are connected to CS2 and CS3, and +V_{ref}, -V_{ref} are connected to CS1 and CS4 respectively. Thus, input voltages are sampled and superimposed to the V_{bias} voltage. During PH2, the left sides of CS1 and CS4 are connected together as are the left sides of CS2 and CS3 and common mode rejection is established. The key advantage of this circuit is; with ideal switches and perfect matching, the samples of V_{common-mode} at the end of PH2 are constant and equal to V_{bias}, independent of the samples of the input and the reference at the end of PH1. Also the preamplifier circuit can be different than the conventional circuits, because the allowed common-mode gain for the preamplifier is increased by the differencing circuit that is used. A tail current source connected in a standard differential-pair may not be required. Thus, eliminating the tail current source would allow an operation at a reduced supply voltage, consecutively low power. The key disadvantage of this circuit is, the differential gain here is about half that of a conventional differencing circuit because four sampling capacitors are required instead of just two. This comparator is a building block of a 3-bits flash ADC in 2-μm CMOS technology with a power supply voltage of 3.3V, a sampling rate of 25MHz, dissipates 1.05mW and occupies 0.25 mm² [34].

A second high-speed comparator is given in Figure 4.25. This is a voltage comparator circuit by Razavi and Wooley [33]. It was realized in 1-μm CMOS
technology with single supply of 5V, it dissipates 0.55mW and its measured input offset is less than 5mV at 5MHz sampling rate. Input offset is cancelled during PH1 phase. In this phase switches S3 through S7 are on, nodes P and Q are charged to Vref+ and Vref-, respectively, and the amplifier's offset is stored on C1 and C2 capacitors. In the transition from this mode to comparison mode, PH1 goes low, turning off switches S3-S7 and turning on S1 and S2. The circuit then begins to regenerate, amplifying the voltage difference between +VIN and -VIN and +Vref and -Vref. Since regeneration begins with M1-M4 already on, its offset voltage is relatively independent of the clock fall time. Nonetheless, if S5-S7 turn off simultaneously any mismatch in the charge injected onto the gates and drains of M1 and M2 can cause false regeneration around M3-M4, resulting in a large input referred offset. In order to avoid this problem, phased clocks are used to turn-on and off the switches as: first turn S3-S6 off to end the reset mode, then turn S1-S2 on to begin the tracking mode and finally turn S7 off to allow regeneration around M3-M4. The clocking scheme of this comparator is too complicated although it is shown as a single clock circuit in Figure 4.25.

Figure 4.25 A comparator by Razavi and Wooley [33].

A third and very suitable voltage comparator example is given in Figure 4.26. This is a comparator circuit by Frank Op’t Eynde and W.Sansen [32]. An experimental version of this comparator has been integrated in a standard double-poly-metal 1.5-μm
n-well process with a die area of only $140 \times 100\mu m^2$. This comparator operates under a $\pm 2.5V$ power supply, performs comparison to a precision of 8-bits, thus its resolution is equal to $\pm 4.9mV$. The highest operation speeds of MOS comparators with 8-bits precision previously introduced than this comparator have been limited to sampling rates of 30MHz for the same technology. But the experimental prototype achieving 8-bit accuracy with the sampling rates up to 65MHz is obtained. The power consumption of the comparator is only 0.85mW at 65MHz clock rate.

Figure 4.26 A fully differential, high-speed voltage comparator [32].

The dynamic operation of this circuit is divided into a reset time interval and a regeneration time interval. The two intervals are approximately between time interval t1 and t2 and between t2 and t4 respectively, as shown in Figure 4.26. During PH2, the comparator is in reset mode. Current flows through the closed resetting switch M12, which forces the previous two logic state voltages to be equalized. After the input stage settle on its decision, a voltage proportional to the input voltage difference is established between nodes a and b in the end. This voltage will act as the initial imbalance for the following regeneration time interval. In the meantime, as the n-channel flip-flop is reset, the p-channel one is also reset by the two closed precharge transistors, which charge
nodes c and d to the positive power supply voltage. As a result the CMOS latch is set to the astable high-gain mode.

![Timing information for the comparator given in Figure 4.26 [32].](image)

Figure 4.27 Timing information for the comparator given in Figure 4.26 [32].

The regeneration phase is initialized by the opening of switch M12. Since the strobing transistors M8 and M9 isolate the n-channel flip-flop from the p-channel flip-flop where PH1 is low, the use of two non-overlapping clocks perform the regenerative process in two steps. The first step of regeneration is within the short time slot between PH2 getting LOW and PH1 getting HIGH. The second regeneration step starts when PH1 gets HIGH and M8-M9 are closed. The n-channel flip-flop, together with the p-channel flip-flop regenerates the voltage differences between nodes a and b and between c and d. The voltage difference between c and d is soon amplified to a voltage swing nearly equal to the power supply voltages. The following SR latch is driven to full complementary digital output levels at the end of the regenerative mode and remains in the previous state in reset mode.

The first regeneration step is very important; not only in raising the regeneration speed but also in reducing the total input offset voltage. The differential errors caused by the charge injection from M8 and M9, mismatches in the p-channel flip-flop, two precharge transistors and the S-R latch are divided by the amplification gain in the first regeneration step, when referred to the input as an equivalent offset voltage. Therefore, their contribution to the total equivalent input offset voltage can be neglected if the gain is large enough.

At the time when PH2 falls, voltages at nodes a and b decrease because if the clock injection, and in the meantime the currents from M1 and M2 charge the two nodes to resume their voltages. Later, as the conductance of switch M12 becomes smaller than
half of the transconductance of M4 and M5, the n-channel flip-flop starts the first step of regeneration. This regeneration process can be approximately analyzed using a small-signal model as shown in Figure 4.28.

![Diagram of regeneration process](image)

Figure 4.28 Regeneration process small signal equivalent [32].

\[
\frac{1}{2} v_{\text{in}g_{m1}} = C_a \frac{dv_a}{dt} + g_{m4}v_b + g_{o12}(v_a - v_b) \quad (4.5)
\]

\[-\frac{1}{2} v_{\text{in}g_{m1}} = C_a \frac{dv_b}{dt} + g_{m4}v_a - g_{o12}(v_a - v_b) \quad (4.6)
\]

In these equations \(v_{\text{in}}\) is equal to \(v_{\text{imp1}} - v_{\text{imp2}}\). Voltages \(v_a\) and \(v_b\) stand for the increments relative to the voltage at nodes a and b with zero input difference. Solving Eq. 4.5 and Eq. 4.6 gives

\[
v_{ab} = [v_{a0} - v_{b0} - g_{m1} / (2g_{o12} - g_{m4})v_{\text{in}}] \exp(v/\tau) + g_{m1} / (2g_{o12} - g_{m4})v_{\text{in}} \quad (4.7)
\]

\[
\tau = C_a / (g_{m4} - g_{o12}) \quad (4.8)
\]

Eq. 4.7 and Eq. 4.8 shows that when \(g_{o12}\) is smaller than half of \(g_{m4}\), \(\tau\) becomes positive and the first regeneration step starts.

To optimise the speed of the first regeneration step, the most efficient way is to minimize the time constant. When M12 is off, the time constant only depends on the capacitance at node a and b and the transconductance of M4 or M5. The capacitance is related to the sizes of M1, M2, M4, M5, M8, M9 and M12.

The voltage difference between nodes a and b reduces very quickly at the beginning of the reset. Later the reduction rate slows down. It will have a local minimum at some instant if the current through M12 is equal to the current through M5 while M4 just reaches the edge of conducting, which should be avoided in high-speed
applications. Therefore, the width of M4 or M5 and M12 should satisfy the inequality of $I_{12} > I_{5}$ at that moment to ensure that there is still some extra current to charge node b. By using a simplified current model, the inequality is

$$\frac{W_{12}}{L \cdot K_{pn}} \left[ (V_{dd} - V_b - V_{Tn12})(V_a - V_b) - 0.5(V_a - V_b)^2 \right] > \frac{W_{5}}{L \cdot K_{pn}} \left[ (V_a - V_{ss} - V_{Tn5})(V_b - V_{ss}) - 0.5(V_b - V_{ss})^2 \right]$$

(4.9)

In the second period of the reset mode, the circuit behavior can be derived using the small signal model given in Figure 4.28. Under the resetting conditions, we obtain

$$v_{ab} = g_{m1} v_{in} / \left( 2g_{o12} - g_{m4} \right) + A \exp(t/\tau_t)$$

$$v_a + v_b = B \exp(\frac{-g_{m4}}{C_t})$$

(4.10)

Eq. 4.7 and Eq. 4.8 indicate that if $2g_{o12}$ is smaller the $g_{m4}$ it is impossible to have the comparator reset. If $2g_{o12} < g_{m4}$ it is impossible to reset the comparator. For the regeneration time optimization, when M12 is off the time constant in the first regeneration step can be written as

$$\tau_{reg} = (\alpha W_4 + C_p) / \sqrt{2L_4 W_4 / L_4 K_{pn}}$$

(4.11)

$\alpha W_4$ represents the capacitance related to the width of M4 or M5, and it will also include the capacitances from M12 and M8 or M9 if W12, W8 and W9 are all chosen to be proportional to W4. The reference current can be increased to raise the comparison speed, however $V_{GS1} - V_{TP1}$ will be larger and a larger offset voltage will result. [32]

Based on the discussions presented in this section, we present a new voltage comparator circuit in the next section that satisfies all of the strict design requirements set by the high speed pipelined ADC architecture specifications.
4.4. Proposed Voltage Comparator Architecture

This chapter presents the design of the novel voltage comparator circuit that is based on a simple symmetric cross-coupled latch structure that operates with a single clock signal. This circuit is capable of responding to a very wide range of input voltages (almost equal to the power supply range of the circuit), that makes it a very attractive option for low-voltage applications. At the same time, the response speed of the proposed comparator circuit is high enough to allow operation at 200 MHz (in fact, up to 1 GHz) sampling clock frequency.

4.4.1 Basic Comparator Circuit

The basic version of the proposed voltage comparator circuit is shown in Figure 4.29. Here, the cross-coupled latch core consisting of M1-M4 produces the output decision based on a small imbalance of the branch currents. The nMOS transistor M5 is used to reset the latch, while M6 and M7 receive the input signals \( V_n \) and \( V_p \). The parallel-connected nMOS transistors M8 and M9 simply provide robust current path for the output latch during the decision phase.

![Figure 4.29 Basic voltage comparator schematic.](image)

The dynamic operation of the circuit is controlled by a single clock signal (CLK). When the clock is HIGH, the output latch (and consequently, the comparator) is in reset
mode. Both output nodes are stabilized at inversion threshold, and the output latch operates at its highest gain point. Meanwhile, the two input voltages $V_n$ and $V_p$ are applied to M6 and M7, producing a slight difference in the drain-to-source voltage levels. When the clock signal returns to zero, M5 releases the cross-coupled latch from its reset mode while M8 and M9 are turned on to provide a robust current path for the latch circuit. The output decision is produced in a very short amount of time based on the previously established current / voltage difference between the two symmetric branches.

![Figure 4.30 Output waveforms of basic voltage comparator circuit.](image)

The typical output voltage waveforms of the basic comparator circuit are shown in Figure 4.30. The input voltage difference reverses its sign in consecutive clock cycles, and the corresponding output decision is generated with a very short response time following the falling edge of the clock signal. The basic comparator circuit has the significant advantages of a very simple structure, small area, relatively high-speed and low power dissipation.
Figure 4.31 Response time vs. input voltage difference.

The output response time of the basic comparator circuit is shown in Figure 4.31 as a function of the input voltage difference $\Delta V$. The response time is seen to increase as the voltage difference becomes smaller, but does not exceed 650 ps even within 2mV of decision threshold. The response time drops significantly, as the input voltage difference becomes larger. Typical response times for $\Delta V = 500$ mV were found to be less than 200 ps when driving a capacitive load of 50 fF on both outputs. Note, however, that this basic comparator circuit cannot produce a reliable output decision when both of the input voltages are below the threshold voltage level of nMOS transistors M6 and M7. Response times for the full input range that can produce a reliable output for the basic comparator circuit can be seen in Figure 4.32. Note that, $V_n$ is held constant at $V_{\text{full\_scale}} / 2$ in this figure.
Figure 4.32 Response time variation along the entire input dynamic range for basic voltage comparator. \( V_{\text{full\_scale}} = 1.8V \)

### 4.4.2 Full Complementary Voltage Comparator

As already mentioned in the previous section the basic comparator circuit suffers from a limited input dynamic range. To further increase the input dynamic range the basic topology is modified with four additional transistors. The circuit diagram of the improved comparator circuit is shown in Figure 4.33.
Figure 4.33 Full-complementary voltage comparator circuit diagram.

The added complementary pMOS transistors in the pull-up path of the latch core act the same way as the nMOS transistors in the pull-down path. During the reset phase, the pMOS transistors driven the input voltages create a small current difference between the two symmetric branches, and during the decision phase, the two pMOS transistors driven by the clock signal establish a current path for the latch circuit. The complementary pMOS transistors become especially important when both input voltages are lower than the threshold voltage of the nMOS transistors. Thus, the circuit has the ability to respond a very wide input dynamic range, which practically extends to full range of the power supply voltage.

After the simulations done to identify the input voltage range that this topology can handle, it is confirmed that almost rail-to-rail input voltage range in 1.8V supply voltage is achievable. This improved comparator topology can produce a reliable output decision in all process corners when 1.6$V_{pp}$ input voltage range is used. It can also produce reliable outputs for typical and best case simulation conditions for 1.8$V_{pp}$ input voltage range for the simulations done from schematic view.

The disadvantage of this topology is the insufficient response times (typically 600 ps) for 200 MHz pipelined A/D converter structure. Still, the complementary comparator with improved input voltage range has the significant advantages of a very simple structure, small area, low power dissipation and almost rail-to-rail input dynamic range.
4.4.3 Improved Full Complementary Voltage Comparator

As already mentioned in the previous section, the improved basic voltage comparator with the full complementary input stage suffers from a limited output response time. To further improve the response speed, the new circuit was modified with four additional transistors. The circuit diagram of the improved complementary comparator circuit is shown in Figure 4.34. The operating principles of the improved full-complementary comparator are exactly the same as the original complementary voltage comparator described in Section 4.4.2, with the exception that the output stage provides significantly better drive capability to improve the response times.

![Diagram of improved full complementary voltage comparator circuit](image)

Figure 4.34 Improved full complementary voltage comparator circuit.

Note that in Figure 4.34, the transistors that correspond to the basic voltage comparator circuit are highlighted. The transistors M10-M13 are used to further improve the output response speed. Note that the CMOS pair at each output node is driven by the output signal of the other output, resulting in an accelerated pull-up (and pull-down) of the corresponding output levels. Figure 4.35 shows the output response time of the improved comparator circuit as a function of the input voltage difference, when both outputs are loaded with 50 fF load capacitance.

79
Figure 4.35 Response time of improved full complementary comparator with respect to input voltage difference.

The response times of the improved complementary comparator circuit were found to be about 150 ps shorter than those of the basic comparator circuit (Figure 4.32) for larger input voltage ranges (which includes threshold levels of both nMOSs and pMOSs). As a result sampling frequencies up to 1 GHz were obtained. The worst case response times for larger input voltage differenced are plotted in Figure 4.36, where one of the input voltage is held constant at $V_{FS} / 2 = 0.9V$, the other input is progressively increased with 10mV steps, and the response times were recorded. It can be seen that the response times exhibit a very symmetric distribution for the entire input range.
Figure 4.36 Response times of the improved full complementary voltage comparator, obtained for the entire input range.

Also response times for different input voltage differences can be seen in Figure 4.37 while one of the input is held constant at LSB reference voltage level (0.1 V) and the other is increased by 100mV voltage steps.

Figure 4.37 Response times obtained for different input voltage differences.

Power consumption of the improved complementary voltage comparator is examined in two different ways. First, consumed power is examined with changing the
voltage difference applied to the two inputs (Figure 4.38), second; power consumption is plotted for different sampling frequencies (Figure 4.39).

![Power Dissipation Graph]

Figure 4.38 Power consumption for different input voltage differences.

![Power Consumption Graph]

Figure 4.39 Power consumption for different sampling frequencies.
The worst-case input voltage offset of the improved complementary comparator was found to be \( \leq 10 \text{ mV} \), allowing conversion with greater than 10-bit accuracy at a dynamic input range of \( 1.6V \text{pp} \). The INL and DNL error values remain within \( \pm 0.1 \text{LSB} \) for this 4-bit application, due to the fact that the maximum offset does not exceed 10 mV. To evaluate the performance of the proposed improved complementary voltage comparator circuit in ADC applications, we have constructed and extensively simulated a four-bit flash A/D converter architecture consisting of a resistor voltage divider chain and fifteen identical comparators (Figure 4.41). Each comparator in the simulated converter chain drives dual CMOS transmission gates, which represent a combined load capacitance of approximately 50 fF. Characterization of the improved full complementary comparator for all three corners (best-typical-worst) in response time, power consumption, integral and differential nonlinearities, offset and also sampling speed simulations were done for the given 4-bit flash topology. These simulation results are given below with detailed information specified underneath each figure. The mask layout of the improved complementary comparator is shown in Figure 4.40. The circuit occupies a silicon area of about 320 \( \mu \text{m}^2 \) in 0.18 \( \mu \text{m} \) CMOS technology.

![Diagram of the improved complementary-in voltage comparator](image)

Figure 4.40 Layout of the improved complementary-in voltage comparator.

83
Figure 4.41 4-bit ADC / MDAC schematic used in improved full complementary voltage comparator verification.

A 4-bit flash ADC and MDAC were simulated for the entire input dynamic range in ideal simulation conditions for all three corners of silicon parameters. Delays of $Q_+$ and $Q_-$ outputs were recorded for the corresponding falling edge of the CLK as well as the delay of the multiplying DAC output. This data obtained for typical corner silicon is given in Figure 4.42. Then, possible mismatch errors that can occur in the input transistors were taken into consideration and simulations modeling these effects were done on the schematic given in Figure 4.41. Mismatch that can occur in nMOS transistors was set to a maximum of ±%3.58 and ±%2.85 for pMOS transistors in the design rule manual for 0.18µm CMOS technology. Thus, three corner simulations were done to identify these effects on comparators with manually mismatched input stages for different input voltage levels. The strategy of these simulations was to apply manual mismatch information to only one input stage transistor at a time. Consequently, nMOS
and pMOS input stages were disturbed independently from each other. Only typical corner simulation results will be given for LSB, MSB and $V_{\text{full scale}} / 2$ voltage levels.

![Comparator Chain Typical Case Simulation](image)

Figure 4.42 Response times for Q, Q̅ and MDAC output voltage in ideal conditions.

![Typical Response Time Simulation with Input Voltage Defined @ LSB Level](image)

Figure 4.43 Response times obtained for input voltage at LSB level, typical corner and nMOS input stage transistors with mismatch.
Figure 4.44 Response times obtained for input voltage at LSB level, typical corner and pMOS input stage transistors with mismatch.

Figure 4.45 Response times obtained for input voltage at $V_{\text{full\_scale}}/2$ level, typical corner and nMOS input stage transistors with mismatch.
Figure 4.46 Response times obtained for input voltage at $V_{\text{full\_scale}}/2$ level, typical corner and pMOS input stage transistors with mismatch.

Figure 4.47 Response times obtained for input voltage at MSB level, typical corner and nMOS input stage transistors with mismatch.
Figure 4.48 Response times obtained for typical corner simulations for 500MHz clock frequency.

From Figure 4.48 to 4.50 the influence of clock frequency can be seen on response time for the improved complementary voltage comparator circuit. Increasing the clock frequency does not result in a significant deterioration of response times. Thus applications are found out to be feasible up to 1 GHz of clock frequency.

With these characteristics, the proposed voltage comparator structure emerges as a good candidate for high-speed Flash A/D converter applications where accuracy and response speed are crucial. In addition, the improved full complementary comparator circuit can utilize the entire power supply range as its dynamic input voltage range, thereby improving its noise performance.

As can be seen from the characteristics given above, the dynamic power dissipation of the basic and improved comparator circuits was also simulated in detail, since power consumption typically represents one of the most important limitations. The only significant power dissipation was observed during the reset phase, when the cross-coupled latch circuit is forced to operate at inversion threshold. When the clock signal switches to zero, the circuit quickly reaches its stable
Figure 4.49 Response times obtained for typical corner simulations for 750MHz clock frequency.

Figure 4.50 Response times obtained for typical corner simulations for 1GHz clock frequency.
decision state and it ceases to conduct current. In terms of power dissipation, the basic voltage comparator circuit is expected to perform better than the improved complementary-in version, since the current path during the reset phase is defined only by M6 and M7 in the basic comparator circuit topology. By contrast, the improved complementary voltage comparator circuit draws a larger amount of current from the power supply because the cross-coupled latch and the external pull-up / pull-down transistors are biased at inversion threshold (saturation current) during the reset phase.

Finally, worst case response times observed at the output nodes of the converters are plotted in Figure 4.51, as a function of the input voltage level, simulated at a clock frequency of 200MHz.

![Graph showing output response time vs. input voltage](image)

Figure 4.51 Worst-case response time vs. input voltage in a simulated 4-bit flash ADC.

Figure 4.52 shows the simulated average power dissipation of the two comparator circuits (basic comparator vs. improved complementary comparator), as a function of the sampling frequency. It is observed that the basic voltage comparator dissipates significantly less power compared to the improved version of the circuit. Still the average power dissipation of the improved complementary-in comparator remains at
about 0.8mW for 200 MHz sampling frequency, and increases to about 1.2mW only at 1 GHz sampling frequency.

Figure 4.52 Average power dissipation of the comparator circuits vs. sampling frequency.

The integral non-linearity (INL) and differential non-linearity (DNL) error worst case values remain within ±0.1 LSB for this 4-bit flash application (typically < ±0.01 LSB), due to the fact that the maximum offset does not exceed 10 mV. Three corner simulations were done to clarify the performance measures such as INL and DNL. Typical corner simulation results can be seen in the graphs provided.
Figure 4.53 Integral non-linearity obtained with improved full complementary comparator for typical simulation corner.

Figure 4.54 Differential non-linearity obtained with improved full complementary comparator for typical simulation corner.

Both INL and DNL graphs obtained for the comparator chain shows peak values at the first and last thermometer codes because of the input related offset of the first and last components of the comparator chain.
4.4.4 Low Power Version of the Complementary Comparator

After determining how much power is dissipated by the improved complementary comparator circuit we decided to find a low-power solution without changing any of the response speed, input-offset and simplicity of the topology.

As already mentioned in the previous section, significant part of power dissipation was observed during the reset phase because of the cross-coupled latch and the external pull-up / pull-down transistors which were implemented in the topology to further improve the response speed. As a result response time and power consumed are two trade-offs of our voltage comparator design.

Response speed being one of the most critical design specification of flash A/D converters and also our A/D converter, which will work at 200 MHz, we do not want to give up the response times we reached. By contrast we also do not want to consume that much power. So, to further reduce the power consumption of the improved complementary comparator circuit we propose the low power version that includes four additional transistors implemented in the output stage to latch the decision levels during the reset mode, which in turn lowers the power dissipated. The low power version of the improved comparator circuit is given in Figure 4.55.

![Comparator circuit with latched output stage during reset mode (Low power comparator version.)](image)

Figure 4.55 Comparator circuit with latched output stage during reset mode (Low power comparator version.)
The latching pMOS transistors are enabled with the clock signal and nMOS transistors with its complementary. During reset phase (while CLK is HIGH) the output is in latch state so that the outputs stay at their previous decision levels. Because there does not exist any DC path for current in this mode, the output stage of the voltage comparator does not consume any power during reset phase. After reset phase in which CLK is LOW, evaluation phase is entered and all the latching MOS transistors are turned-on and a new decision is made within very small time interval.

By the simulations done it is found out that power consumption of the improved complementary version is halved in this low power version. But in return response times increase about 50 ps. The input offset is also increased due to the clock feedthrough from the latch transistors implemented. So we decided to use the improved full complementary version presented in Section 4.4.3 in our 12-bit pipelined A/D converter structure, despite the higher power dissipation.
5. ARCHITECTURE COMPONENTS: HIGH-SPEED OP-AMP DESIGN

5.1 Introduction of Basic Concepts

An important analog building block, especially in data-converter systems, is the sample-and-hold circuit. Before proceeding, it is worthwhile to mention that sample-and-hold circuits are also referred to as “track-and-hold” circuits. Normally, these two terms are synonymous except for a few switched-capacitor sample-and-hold circuits that do not have a phase where the output signal is tracking the input signal. Sample-and-hold circuits are necessary components in many data-acquisition systems such as A/D converters. In many cases, the use of sample and hold (at the front of the data converter) can greatly minimise errors due to slightly different delays times in the internal operation of the converter [2].

Before discussing the basic principles of sample-and-hold circuits, it is necessary to mention some performance parameters used in characterisation.

- The first of these parameters is a sampling pedestal or a hold step. This is an error that occurs each time a sample and hold goes from sample mode to hold mode. During this change in operation, there is always a small error in the voltage being held that makes it different from the input voltage at the time of sampling. Obviously, this error should be as small as possible. Perhaps more importantly, this error should be signal independent; otherwise it can introduce nonlinear distortion (Figure 5.1).
Another parameter is a measure of how isolated the sampled signal from the input signal during hold mode. Ideally, the output voltage will no longer be affected by changes in the input voltage. In reality, there is always some signal feedthrough, usually through parasitic capacitive coupling from the input to the output. In well-designed sample and holds, the signal feedthrough can be greatly minimised.

A third important parameter is the speed at which a sample and hold can track the input signal, when in sample mode. In this mode, a sample and hold will have both small-signal and large-signal limitations due to its -3dB bandwidth and finite slew rate, respectively. Both -3dB bandwidth and slew rate should be maximised for high-speed operations (Figure 5.1).

Yet another limitation (somewhat less important in high-speed designs) is the droop rate in hold mode. This error is a slow change in output voltage, when in hold mode, caused by effects such as leakage currents due to the finite base
currents of bipolar transistors and reversed-biased junctions. In most CMOS designs, this droop rate is so small it can be often be ignored (Figure 5.1).

➢ A fifth limitation is aperture time uncertainty. This error is the result of the effective sampling time changing from one sampling instance to the next and becomes more pronounced for high-speed signals. Specifically, when high-speed signals are being sampled, the input signal changes rapidly, resulting in small amounts of aperture uncertainty causing the held voltage to be significantly different from the ideal held voltage (Figure 5.1) [2].

Other performance parameters are also important when realizing sample and hold circuits. These include parameters such as dynamic range, linearity, gain, and offset error.

Operational amplifiers (op-amps), being the heart of the sample-and-hold circuits, will be examined deeply hereafter. In addition to the classic sample-and-hold function, a pipelined A/D converter architecture also requires fast and accurate amplification of the residue signal at the end of each pipeline stage. Again, a highly linear op-amp with small offset and high slew rate is preferred for this function.

We loosely define an op-amp as a “high-gain differential amplifier”. By “high” we mean a value that is adequate for the application, typically in the range of $10^1$ to $10^5$. Since op-amps are usually employed to implement a feedback system, their open-loop gain is chosen according to the precision required of the closed-loop circuit.

Up to two decades ago, op-amps were designed to serve as “general-purpose” building blocks, satisfying the requirements of many different applications. Such efforts brought to create an “ideal” op-amp with very high voltage gain (several hundred thousand), high input impedance and low output impedance, but at the cost of many other aspects of the performance, e.g., speed, output voltage swing, and power dissipation.

By contrast, today’s op-amp design proceeds with the recognition that the trade-offs between parameters eventually require a multi-dimensional compromise in the overall implementation, making it necessary to know the adequate value that must be achieved for each parameter. For example, if the speed is critical while the gain error is not, a topology is chosen that favours the former, possibly sacrificing the later.
Figure 5.2 Behavioral model for ideal differential input, single-ended output op-amp[1].

Ideally, an op-amp has infinite differential voltage-gain, infinite input resistance, and zero output resistance as shown in Figure 5.2. In practice, the operational amplifier only approaches the ideal characteristics. Some of its other non-ideal characteristics are illustrated in Figure 5.3. The finite differential-input impedance is modelled by \( R_{id} \) and \( C_{id} \). The output resistance is modelled by \( R_{out} \). The common-mode input resistances are given as resistances of \( R_{icm} \), connected from each of the input to ground. \( V_{os} \) is the input-offset voltage necessary to make the output voltage zero if both the inputs of the op-amp are grounded.

\( I_{os} \) (not shown) is the input-offset current, which is necessary to make the output voltage zero if the op-amp is driven from two identical current sources. Therefore, \( I_{os} \) is defined as the magnitude of the difference between the two input-bias currents \( I_{b1} \) and \( I_{b2} \). Since the bias currents for a CMOS op-amp are approximately zero, the offset current is also zero. The common-mode rejection ratio (CMRR) is modelled by the voltage controlled voltage source indicated as \( V_{1}/CMRR \). This source approximately models the effects of common-mode input signal on the effects of common-mode input signal on the op-amp. The two sources designated as \( e_n^{-2} \) and \( I_n^{-2} \) are used to model the
op-amp noise. These are voltage- and current-noise spectral densities with units of mean square volts and mean square amperes, respectively [3].

Figure 5.3 A model for an ideal op-amp showing some of the nonideal characteristics [3].

Not all of the non-ideal characteristics of the op-amp are shown in Figure 5.3 [6]. Other pertinent characteristics of the op-amp will now be defined. The output voltage of Figure 5.2 can be defined as

\[ V_{out}(s) = Av(s)[V^+(s) - V^-(s)] + Ac(s) \frac{V^+(s) + V^-(s)}{2} \]  

(5.1)

where the first term on the right is the differential portion of Vout(s) and the second term is the common-mode portion of the Vout(s). The differential-frequency response is given as \( Av(s) \) while the common-mode frequency response is given as \( Ac(s) \). A typical differential-frequency response of an op-amp is given as

\[ Av(s) = \frac{Av_0}{\left( \frac{s}{p_1} - 1 \right) \left( \frac{s}{p_2} - 1 \right)} \]  

(5.3)
where \( p_1, p_2, \ldots \) are poles of the operational amplifier (op-amp) open-loop transfer function. In general, a pole designated as \( p_i \) can be expressed as

\[
 p_i = -\omega_i
\]

(5.4)

where \( \omega_i \) is the reciprocal time constant or break-frequency of the pole \( p_i \). While the op-amp transfer function may have zeros, they will be ignored now. \( A_v(0) \) is the gain of the op-amp as the frequency approaches zero. Figure 5.4 shows a typical frequency response of the magnitude of \( A_v(s) \). In this case we see that \( \omega_1 \) is much lower than the rest of the break-frequencies causing \( \omega_1 \) to be the dominant influence in the frequency response. The frequency where the \(-6\)dB/oct slope from the dominant pole intersects with the 0dB axis is designated as the unity-gain bandwidth, abbreviated GB, or GBW, of the op-amp.

![Graph of the magnitude of A_v(s) vs. frequency](image)

**Figure 5.4 Typical frequency response for an op-amp [3].**

Other non-ideal characteristics of the op-amp not defined by Figure 5.3 include the power-supply rejection ratio, PSRR. The PSRR is defined as the product of the ratio of the output voltage of the op-amp caused by the change in power supply and the open-loop gain of the op-amp. Thus,
\[ PSRR = \frac{\Delta V_{DD}}{\Delta V_{out}} \ast A_c(s) = \frac{V_o}{V_{in}} \frac{V_o}{V_{in}} \frac{V_o}{V_{DD}} \]

The common-mode input range is the voltage range over which the input common-mode signal can vary. Typically, this range is several volts less than \( V_{DD} \) and several volts more than \( V_{SS} \).

The output of the op-amp has several important limits, one of which is the maximum output current sourcing and sinking capability. There is a limited range over which the output voltage can swing while still maintaining high-gain characteristics. The output also has a voltage rate limit called slew rate. The slew rate is generally determined by the maximum current available to charge or discharge a capacitance. Normally, slew rate is not limited by the output, but by the current-sourcing capability of the first stage. The last characteristic of importance in analog sampled-data circuit applications is the settling time. This is the time needed the output of the op-amp to reach a final value (to within a predetermined tolerance) when excited by a small signal. This is not to be confused with slew rate, which is large-signal phenomenon. Many times, the output response of an op-amp is a combination of both large- and small-signal characteristics. Small-signal settling time can be completely determined from the location of the poles and zeros in the small-signal equivalent circuit whereas slew rate is determined from the large signal conditions of the circuit.

The importance of the settling time to analog sampled-data circuits is illustrated by Figure 5.4. It is necessary to wait until the amplifier has settled to within a few tenths of a percent of its final value in order to avoid errors in the accuracy of the processing analog circuits. A longer settling time implies that the rate of the processing analog signal must be reduced.

Fortunately the CMOS op-amp does not suffer from all of the nonideal characteristics previously discussed. Because of the extremely high input resistance of the MOS devices, both \( R_{id} \) and \( I_{bs} \) are of no importance. A typical value of \( R_{id} \) is in the range of \( 10^{14} \) ohms. Also \( R_{ion} \) is extremely large and can be ignored.

Before the actual design of an op-amp can begin, though, one must set out all of the requirements and boundary conditions that will be used to guide the design. The fundamental boundary conditions and specifications are listed below, in Table 5.1. Note
that the typical values (expected values) given here are intended for an op-amp that is
designed using a single power supply (1.8 V), and that should be capable of handling
tasks such as high-speed sampling and amplification (at frequencies above 200 MHz)
while driving a relatively small on-chip capacitive load. The design trade-offs that are
involved for the realization of the indicated specifications are also listed in Table 5.1,
emphasizing the fact that the improvement of one particular specification is usually
dependent on other parameters that must be sacrificed.

Boundary conditions:
* Process specifications ($V_T$, $K$, $C_{ox}$, etc.)
* Supply voltage range
* Supply current range
* Operating temperature and range.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Typical Requirements</th>
<th>Trades-off with</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gain</td>
<td>$\geq 70$ dB</td>
<td>Linearity, PSRR</td>
</tr>
<tr>
<td>Gain Bandwidth</td>
<td>$\geq 500$ MHz</td>
<td>SR, Offset</td>
</tr>
<tr>
<td>Settling Time</td>
<td>$\leq 1$ ns</td>
<td>SR, GBW</td>
</tr>
<tr>
<td>Slew Rate</td>
<td>$\geq 1$ V / ns</td>
<td>GBW, Settling time</td>
</tr>
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<td>Input CMR</td>
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</tr>
<tr>
<td>CMRR</td>
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<td></td>
</tr>
<tr>
<td>PSRR</td>
<td>$\geq 60$ dB</td>
<td></td>
</tr>
<tr>
<td>Output Swing</td>
<td>$\geq 1.4$ V&lt;sub&gt;pp&lt;/sub&gt;</td>
<td>Noise, Settling time, GBW, SR</td>
</tr>
<tr>
<td>Output Resistance</td>
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<td>Output-voltage swing</td>
</tr>
<tr>
<td>Offset</td>
<td>$\leq \pm 10$ mV</td>
<td>Gain, GBW</td>
</tr>
<tr>
<td>Noise</td>
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<td>Output-voltage swing</td>
</tr>
<tr>
<td>Layout area</td>
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<td>Gain</td>
</tr>
</tbody>
</table>

Table 5.1 Typical specifications of a CMOS op-amp.
5.2 OTA Based Op-Amp Design Flow

An operational transconductance amplifier (OTA) given in Figure 5.5, also called a transconductance element or a transconductor, is a device that translates voltage inputs to current outputs, such that $i_{out} = G_m v_{IN}$. Recently, OTAs have emerged as compelling alternatives to conventional op-amps in the realisation of fully integrated continuous-time active filters. Part of the interest in OTAs stems from their relative simplicity in comparison to a standard op-amp circuits. For example, CMOS OTAs are single stage circuits, essentially comprised of a simple differential stage. Hence, at high frequencies where large excess phase significantly degrades the performance of a conventional op-amp, a properly designed OTA can still maintain near ideal behaviour.

![Figure 5.5 The differential OTA symbol and ideal model [1].](image)

An OTA has a large open-loop output resistance at low frequencies. Its gain is characterised by a transconductance $G_m$ that can be quite large.

Manual analysis of a symmetrical CMOS OTA will be examined in detail in the following paragraphs.

The circuit schematic of the CMOS OTA with symmetrical input stage is given in Figure 5.6. The differential pair is formed by input transistors M1 and M2. They drive their output currents in two transistors, M3 and M4, which are connected as diodes. They are the inputs of two current mirrors with current multiplication factor $B$. Typical values are $B = 1$ to $3$. The output current of transistor M5 (see Figure 5.6) is then mirrored once more in current mirror M7, M8, with $B = 1$, as indicated [1].
Gain of the symmetrical CMOS OTA: At nodes 4, 5, and 6, a diode connected MOS is driven by a current source. A diode connected MOS represents only a small signal resistance of \( \frac{1}{g_m} \), whereas the current source has an output resistance \( r_s \), which is much higher than \( \frac{1}{g_m} \). As a result, at each of these nodes, the small-signal resistance with respect to ground is quite small, i.e. \( \frac{1}{g_m} \).

The small-signal resistance is high only at the output node 7. It is formed by the two output resistances of \( r_{o6} \) and \( r_{o8} \) in parallel. For equal values of \( r_{o6} = r_{o8} \), output resistance \( R_{OUT} \) equals \( r_{o6}/2 \). On the other hand, the transconductance of symmetrical OTA is \( g_{m1} \).

The voltage gain \( A_v \) is then given by multiplication of transconductance and \( R_{OUT} \), or by Eq. 5.6.

\[
A_v = B \times g_{m1} \times R_{OUT} = \frac{2 \times K_s \times \begin{Bmatrix} W \\ L \end{Bmatrix}}{I_B} \times \left( r_{o6} // r_{o8} \right)
\]  
(5.6)
Note that factor B is not present in the expression of the gain $A_v$. The transconductance increase B times whereas $R_{OUT}$ decreases B times. The voltage gain $A_v$ can thus be increased by increasing $r_{06}$ or $r_{08}$. With this additional degree of freedom, the output resistance $R_{OUT}$ and the voltage gain $A_v$ can be increased without effecting OTAs transconductance.

Up until this point, the total gain $A_v$ of the OTA has been considered. The gain of the first stage $A_{v1}$ alone is also important as well, as it determines the noise performance of the OTA. It is given by the ratio of $(v_3 - v_4) / v_{IN1}$, if $v_{IN2}$ is grounded. It is found by inspection to be

$$A_{v1} = \frac{g_{m1}}{g_{m3}} = \sqrt{\frac{K_n'}{K_p} \left[ \frac{W}{L_1} \right]}$$

(5.7)

For the noise purposes, we must ensure that the noise of the input stage is dominant over the noise of the output transistors referred to the input. Therefore, the gain must be larger than unity, i.e. the gain must have a minimum value of three, the reasons for which will be explained shortly [1].

**GBW of the symmetrical CMOS OTA:** The values of the dominant and nondominant poles can be determined as well as the value of the GBW (Gain Bandwidth). There exist more nondominant poles than a simple OTA because of the higher number of signal carrying nodes. They must be shifted to sufficiently high frequencies in order to ensure a phase margin (PM) of more than 60°.

The dominant pole $f_d$ is evidently realised at node 7, which exhibits the highest resistance, i.e. $R_{OUT}$. Its value is given by

$$f_d = \frac{1}{2\pi R_{OUT} (C_{n7} + C_L)}$$

(5.8)

in which $C_{n7}$ includes all parasitic capacitances connected to node 7, due to the OTA (see Figure 5.6). The value of GBW is given by
\begin{equation}
\text{GBW} = A, f_d = \frac{B g_{m1}}{2\pi (C_{n7} + C_L)} = B \frac{\sqrt{2} K_p I_B}{2\pi} \frac{\sqrt{W/L_1}}{C_{n7} + C_L}
\end{equation} (5.9)

the value of GBW is increased by the design parameter B at the expense of more current consumption. In order to be able to effectively use this value of GBW, the nondominant poles are evaluated first. The calculation of phase margin will show that the factor of B can never be made large [1].

**Phase margin (PM) of the symmetrical CMOS OTA:** Nondominant poles occur at all other nodes, i.e. at nodes 4, 5, and 6, due to the capacitances on these nodes. Nodes 4 and 5 carry small signals, which have the same amplitude but the opposite phase. Therefore, the poles at nodes 4 and 5 are the same. Together, they form one single nondominant pole \( f_{nd5} \). It is found by inspection and is given by

\begin{equation}
f_{nd5} \approx \frac{g_{m5}}{2\pi C_{n5}} = \frac{\sqrt{2} K_p I_B}{2\pi} \frac{\sqrt{W/L_4}}{C_{n5}}
\end{equation} (5.10)

The other nondominant pole occurs at node 6, i.e. \( f_{nd6} \), but acts on only half of the output signal. Indeed, only the current flowing in M3, M5, M7, and M8 is subject to this pole. A thorough analysis shows that, when a pole acts on only half of the signal, a zero must be added at twice the frequency. A pole-zero doublet is thus created. This pole is again found by inspection and is given by

\begin{equation}
f_{nd6} \approx \frac{g_{m7}}{2\pi C_{n6}} = \frac{\sqrt{2} K_p I_B}{2\pi} \frac{\sqrt{B(W/L_7)}}{C_{n6}}
\end{equation} (5.11)

\( f_{z6} = 2f_{nd6} \)

The value of phase margin is given in Eq. 5.12.
\[ PM = 90^\circ - \varphi_{n5} - \varphi_{n6} \]

\[
where \quad \varphi_{n5} = \arctan \frac{BA}{1} \frac{C_{n5}}{C_{L} + C_{n7}}
\]

\[
and \quad \varphi_{n6} = \arctan \frac{\left| B \left( \frac{W}{L} \right) \right|}{C_{n6}} - \arctan \frac{1}{2} \left( \frac{\left| B \left( \frac{W}{L} \right) \right|}{C_{n7}} \right) - \arctan \frac{1}{2} \left( \frac{\left| B \left( \frac{W}{L} \right) \right|}{C_{n7}} \right)
\]

It can be noted that the phase margin can be increased by

* decreasing node capacitances \( C_{n5} \) and \( C_{n6} \)
* decreasing \( B \)
* increasing \( \left( \frac{W}{L} \right) \)

provided we keep \( A_{\alpha1} \) and \( C_{L} \) constant.

It is not acceptable to decrease \( B \) too much. Factor \( B \) is normally increased to increase the slew rate (to be explained later). A good compromise is \( B = 3 \). For a given \( C_{L} \), this leaves us thus only \( \left( \frac{W}{L} \right) \) to adjust in order to ensure sufficient phase margin.

However, the phase margin is not very sensitive to \( \left( \frac{W}{L} \right) \), because \( \varphi_{n6} \) is only a weak function of \( \left( \frac{W}{L} \right) \) [1].

**Slew rate:** Slew rate of a symmetrical CMOS OTA is determined by the load capacitance \( C_{L} \). The current available to charge this capacitance is \( B I_{B} \), thus, the slew rate can be given as in Eq. 5.13.

\[
SR = B \frac{I_{B}}{C_{L} + C_{n7}}
\]

Factor \( B \) can be used to increase the slew rate of the symmetrical CMOS OTA in the excess of current consumption determined as \((1+B) I_{B}\) [1].

**Noise performance:** The total output noise voltage power \( d^2 V_{out} \) is the sum of the equivalent input noise voltage powers \( d^2 V_{in} \) of each transistor, multiplied by their gain squared. The equivalent input noise voltage power \( d^2 V_{in} \) then obtained by division of the total gain squared. Excess noise \( \gamma \) is the normalised total equivalent input noise to equivalent input noise of one of the input transistors can be given as in Eq. 5.14.
\[ y = 2 \left\{ \frac{1}{A_{v1}} \left[ 1 + \frac{1}{B} \left( 1 + \sqrt[7]{\frac{K_r (W/L)}{K_n (W/L)}} \right) \right] \right\} \] (5.14)

The total equivalent input noise can thus be reduced to the equivalent input noise of only the two transistors provided the gain of the first stage \( A_{v1} \) is large. Since this implies lower stability, as shown in Eq. 5.12, a compromise is taken for \( A_{v1} \), such as three to five. Increasing \( B \) helps, but it also reduces the phase margin, thus a good compromise for \( B \) is one to three.

We need to convert current output of the symmetrical CMOS OTA into voltage thus, we used an inverter with a feedback resistor and a Miller compensation capacitance placed between input and output nodes of that inverter. Manual analysis of this inverter will be examined here after [1].

### 5.3 Inverter-Based Output Stage Frequency Analysis

![Inverter-based output stage schematic](image)

Figure 5.7 Inverter-based output stage schematic.

We use a CMOS inverter as given in Figure 5.7 in order to convert the current output of the symmetrical CMOS OTA in to voltage output. An inverter topology was choosen in order to have rail-to-rail output swing that is essential for both the sample-
and-hold and residue amplifiers. Simplicity of the topology, easily obtained high gain, almost rail-to-rail input and output swing properties were the leading specialities of such an architecture. A feedback resistor is used to establish analog output in between the input node and output nodes of inverter, which will degrade the inverters operational characteristics considerably. Using a feedback resistor between input and output of an inverter will obviously decrease the voltage gain, but still sufficient enough for our purpose. Frequency response of such a circuit will be examined hereafter.

Miller compensation is also used for enough phase margin thus the circuit will be simplified into a two pole system with the help of Miller conversion. Small signal equivalent of the inverter given in Figure 5.7 can be seen in Figure 5.8. Manual analysis will be carried on this schematic now on. We used Miller theorem in order to derive the poles and zeros of the inverter based output stage. (Figure 5.9)

![Figure 5.8 Simplified small signal equivalent of the inverter [26].](image)

By simply writing the RC equivalents of both independent parts in Figure 5.9, poles and zeros can be found out. From the input part

![Figure 5.9 Equivalent circuit of Figure 5.8 [26].](image)
\[ z_1 = \frac{-1}{R_f \left( C_i + \frac{C_f}{1 - A_v} \right)} \]

\[ z_1 = \frac{-\left( \frac{R_f}{1 - A_v} + R_i \right)}{R_i \frac{R_f}{1 - A_v} \left( C_i + \frac{C_f}{1 - A_v} \right)} \]

From the second part we obtain:

\[ z_2 = \frac{r_o + \left( \frac{R_f}{1 - \frac{1}{A_v}} \right)}{C_v + \left( \frac{C_f}{1 - \frac{1}{A_v}} \right) r_o \frac{R_f}{1 - \frac{1}{A_v}}} \]

(5.16)

Thus it is proved out that the inverter with feedback resistance and capacitor gives two poles and one zero in the frequency domain.

After deriving out the AC characteristics of such an inverter used in a feedback architecture, we found out that the op-amp formed by symmetrical OTA cascaded to an inverter has five poles and two zeros. Special care must be taken for stability issues in the required bandwidth.

5.4 OTA Based High-Gain Op-Amp Design

An op-amp with high open loop gain, high slew rate, small input / output offset, highly linear and stable for a very wide frequency range is needed for amplifying the residue voltage in each pipeline stage.

This op-amp will be used in a negative feedback with a feedback gain of eight (refer to Chapter 6). Absolute value of the feedback gain is so critical that it could effect
directly the INL, DNL of the over all analog-to-digital converter. Applied resistive feedback will result in a closed loop gain of

\[ A_v = \frac{A_{v0}}{1 + \beta A_{v0}} \]  

(5.17)

where \( \beta \) is the loop gain and \( A_{v0} \) is the open loop gain of the op-amp. Eq. 5.17 can easily be simplified as \( \frac{1}{\beta} \) if \( A_{v0} \) is sufficiently large. Otherwise there will arise amplifying gain error inevitably that will result in degradation in converter performance directly. High slew rate is essential in high-speed pipeline A/D converters because the amplified residue will be used as the analog input signal for the proceeding pipeline stage. Thus, it has to settle to a specified – tolerable – range with in a very small period of time. Output offset has to be minimized, otherwise the value of the analog signal that will be processed in the next stage will totally be different from the analog signal formed in the proceeding pipeline stage from the residue. The op-amp will be used in a feedback loop, thus it has to be stable in a wide frequency range, at least satisfying the Nyquist rate condition, in order to avoid any ringing or oscillation in application. What is more almost rail-to-rail output swing is also necessary for an op-amp to be used as a residue amplifier, because out of this amplifier will be processed as the input analog signal, which represents the held analog input applied to the pipeline stage’s input. If direct concatenation of produced digital bits used to form the valid output of the A/D converter.

Consequently, we have to design an op-amp satisfying all the specifications dictated above for an application at 200MHz sampling rate.
Figure 5.10 High open loop-gain OTA based op-amp schematic [26].

<table>
<thead>
<tr>
<th></th>
<th>$W$ (μm)</th>
<th>$L$ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M1$</td>
<td>10</td>
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</tr>
<tr>
<td>$M2$</td>
<td>10</td>
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</tr>
<tr>
<td>$M3$</td>
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</tr>
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<td>$M4$</td>
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<td>$M5$</td>
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<td>$M6$</td>
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<td>$M8$</td>
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</tr>
<tr>
<td>$C_f$</td>
<td></td>
<td>50 fF</td>
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</table>

Table 5.2 Aspect ratio table for high open loop-gain OTA.
The designed op-amp satisfies all the specification for a residue amplifier. But in unity gain configuration needed for sample-and-hold circuit, op-amp given in Figure 5.10 has stability problems because of the poor phase margin. In addition to poor stability, the unity gain configuration suffers from a limited output voltage swing due to the fact that the first stage OTA can only provide an output voltage that is limited by the amount of one threshold voltage from both rails. Thus, we decided to lower the open loop-gain to establish stability and use the op-amp in a configuration with a negative feedback gain of two, in order to overcome output swing limitation. We did not give up with using this high open loop-gain configuration because we also need a residue amplifier to achieve analog pipelining between two pipeline stages. This residue amplifier must be used in a configuration of feedback gain of 16 without error correction or 8 with error correction (refer to Chapter 6) for a 4-bit A/D pipeline stage. Stability problem of this topology is eliminated by using it in a feedback loop with high voltage gain that is a must in a residue amplifier. Simulation results are given for both DC and AC characteristics in Figure 5.11 to Figure 5.14.

Figure 5.11 DC characteristics of high open loop gain OTA based op-amp.
Figure 5.12 Open loop AC characteristics of high open loop gain OTA based op-amp.

Figure 5.13 Closed loop AC characteristics of high open loop gain OTA based op-amp.
Figure 5.14 Transient characteristics of high open loop gain OTA used in a X16 feedback gain for residue amplifier for a 200MHz 100mV$_{pp}$ input pulse.

<p>| | |</p>
<table>
<thead>
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</tr>
<tr>
<td><strong>Open loop gain</strong></td>
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<td><strong>f$_{180}$</strong></td>
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<td>2.92098 GHz</td>
</tr>
<tr>
<td><strong>Closed loop f$_{3dB}$</strong></td>
<td>2.53 GHz</td>
</tr>
<tr>
<td><strong>Slew rate</strong></td>
<td>2.7523 V/ns</td>
</tr>
</tbody>
</table>

Table 5.3-a Simulation results of the most important specifications.
<table>
<thead>
<tr>
<th>Pole frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>50.7355 MHz</td>
<td>53.88729 MHz</td>
</tr>
<tr>
<td>$p_2$</td>
<td>492.689 MHz</td>
<td>795.52 MHz</td>
</tr>
<tr>
<td>$p_3$</td>
<td>551.1578 MHz</td>
<td>3.6377 GHz</td>
</tr>
<tr>
<td>$p_4$</td>
<td>764.5468 MHz</td>
<td>6.59124 GHz</td>
</tr>
<tr>
<td>$p_5$</td>
<td></td>
<td>13.213 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zero frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$z_1$</td>
<td>490.7125 MHz</td>
<td>2.8456 GHz</td>
</tr>
<tr>
<td>$z_2$</td>
<td>771.8586 MHz</td>
<td>25.526 GHz</td>
</tr>
</tbody>
</table>

Table 5.3-b Comparison of simulated and manually calculated pole/zero frequencies.

There still exists a severe problem for high open loop gain OTA based op-amp. As shown in Figure 5.14 transient response of the amplifier can not reach the rails of the input analog signal. Thus, there will exist systematic conversion errors, which can be corrected by using a very simple, digital error correction algorithm, named as bit overlapping instead of cascading the 4-bit outputs of successive pipeline stages. However, this technique requires higher resolution in the comparator chain of the internal successive pipeline stages. In other words analog input voltage swing range for the internal successive stages have to be halved (refer to Chapter 6). Thus, a feedback gain of “8” is required instead of “16”. We now have to design an op-amp to be used in negative feedback loop with gain “8”.

We have to reduce the feedback gain from “16” to “8”, thus we have to design a more stable op-amp than the previous one. Otherwise we could face stability problems in feedback configuration. On the other hand we also need high open loop gain in order to overcome any gain error that can arise from low loop gain of the feedback configuration. Thus, we increased the compensation capacitance value from 50 fF to 100 fF, which will in turn lower the slew rate of the op-amp. In order to overcome some of this side effect we decreased the value of feedback resistor from 75 kΩ to 50 kΩ that will also reduce the parasitic capacitance of the resistor. All other elements of the architecture stayed the same as the high open loop gain op-amp (Table 5.4). Simulation results of X8 op-amp are given in Figure 5.15 to Figure 5.18.
<table>
<thead>
<tr>
<th></th>
<th>(W (\mu m))</th>
<th>(L (\mu m))</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>M2</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>M3</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>M4</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>M5</td>
<td>3.6</td>
<td>0.18</td>
</tr>
<tr>
<td>M6</td>
<td>3.6</td>
<td>0.18</td>
</tr>
<tr>
<td>M7</td>
<td>2</td>
<td>0.18</td>
</tr>
<tr>
<td>M8</td>
<td>2</td>
<td>0.18</td>
</tr>
<tr>
<td>M9</td>
<td>7.2</td>
<td>0.18</td>
</tr>
<tr>
<td>M10</td>
<td>18</td>
<td>0.18</td>
</tr>
<tr>
<td>(R_f)</td>
<td></td>
<td>50 k(\Omega)</td>
</tr>
<tr>
<td>(C_f)</td>
<td></td>
<td>100 f(\text{F})</td>
</tr>
</tbody>
</table>

Table 5.4 Aspect ratio table for X8 OTA based op-amp configuration.

Figure 5.15 DC characteristics of X8 OTA based op-amp.
Figure 5.16 Open loop AC characteristics of X8 OTA based op-amp.

Figure 5.17 Closed loop AC characteristics of X8 OTA based op-amp
Figure 5.18 Transient response of X8 OTA based op-amp to a 200MHz 100mV_{pp} input pulse.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input offset</td>
<td>1.20 mV</td>
</tr>
<tr>
<td>Output offset</td>
<td>144.82 mV</td>
</tr>
<tr>
<td>I_{R}</td>
<td>50 µA</td>
</tr>
<tr>
<td>Open loop gain</td>
<td>48.2797 dB</td>
</tr>
<tr>
<td>f_{3dB}</td>
<td>1.0484 GHz</td>
</tr>
<tr>
<td>f_{0}</td>
<td>2.1626 GHz</td>
</tr>
<tr>
<td>Closed loop f_{3dB}</td>
<td>665.154 MHz</td>
</tr>
<tr>
<td>Slew rate</td>
<td>1.1209 V/ns</td>
</tr>
</tbody>
</table>

Table 5.5-a Simulation results of the most important specifications.
<table>
<thead>
<tr>
<th>Pole frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>38.21138 MHz</td>
<td>52.28104 MHz</td>
</tr>
<tr>
<td>$p_2$</td>
<td>38.21138 MHz</td>
<td>795.52 MHz</td>
</tr>
<tr>
<td>$p_3$</td>
<td>492.266 MHz</td>
<td>2.0274 GHz</td>
</tr>
<tr>
<td>$p_4$</td>
<td>555.83 MHz</td>
<td>11.4516 GHz</td>
</tr>
<tr>
<td>$p_5$</td>
<td>764.603 MHz</td>
<td>13.213 GHz</td>
</tr>
<tr>
<td>Zero frequency</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$z_1$</td>
<td>42.374 MHz</td>
<td>1.68194 GHz</td>
</tr>
<tr>
<td>$z_2$</td>
<td>490.69 MHz</td>
<td>26.426 GHz</td>
</tr>
<tr>
<td>$z_3$</td>
<td>771.861 MHz</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.5-b Comparison of simulated and manually calculated pole/zero frequencies.

The only drawback of this op-amp is output offset but still in tolerable limits. Thus, we will keep this architecture for the residue amplifier to be used in each pipeline stage with bit overlapping in the digital pipeline.

5.5 OTA based Low-Gain Op-Amp Design

After finishing the design of residue amplifier we now have to design a stable operational amplifier for the sample-and-hold circuit. This op-amp has to be stable in unity gain feedback configuration, which is named as the worst possible configuration for the stability. For this purpose we have to reduce the open loop gain by reducing the input transistors aspect ratio and also the B factor of the pMOS current mirrors, which will also reduce the parasitic capacitances in return, consequently higher the pole frequencies that could cause instability. We need a real sample-and-hold circuit for our purpose (not a track-and-hold amplifier), because we have to process the analog input during half of the sampling clock period. Thus, we will use two stable op-amps cascaded, operated with a non-overlapping clock consequently, which will realise the hold operation. We designed the OTA based op-amp given in Figure 5.19 the element aspect ratios are given in Table 5.6.
Figure 5.19 Schematic view of low open loop-gain OTA.

<table>
<thead>
<tr>
<th></th>
<th>$W$ ($\mu$m)</th>
<th>$L$ ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M1$</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>$M2$</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>$M3$</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>$M4$</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>$M5$</td>
<td>0.72</td>
<td>0.18</td>
</tr>
<tr>
<td>$M6$</td>
<td>0.72</td>
<td>0.18</td>
</tr>
<tr>
<td>$M7$</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>$M8$</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>$M9$</td>
<td>14.4</td>
<td>0.18</td>
</tr>
<tr>
<td>$M10$</td>
<td>36</td>
<td>0.18</td>
</tr>
<tr>
<td>$R_f$</td>
<td></td>
<td>75 k$\Omega$</td>
</tr>
</tbody>
</table>

Table 5.6 Aspect ratio table for low open loop-gain OTA.
After deciding to reduce open loop gain we lowered the pMOS current mirror gain from 10 to 3. In order to satisfy the input offset specification we also lowered the transconductance ($g_m$) of the input stage and aspect ratio of the nMOS current mirror. We end up with a transistor width of 0.28 $\mu$m for nMOS current mirror, which is not feasible. So that we kept the aspect ratio as it was and scaled nMOS current mirror to minimum possible W value. In order to lower the input offset we had to decrease pMOS current gain once more from 3 to 2, which in return lower the open loop gain, higher the phase margin and the output offset. But still very suitable for times two feedback gain configuration to used in sample-and-hold circuit. We inserted this design is a X2 negative feedback configuration having an absolute resistor ratio of two. There we faced gain error because of the low open loop gain of op-amp and also low valued feedback resistors, which steal current from, output stage that results in lower output voltage swing. In order to solve this problem we have to first increase resistor values, resulting in a lower phase margin which will create stability problems. Secondly we have to find a ratio of feedback resistors that will clearly give X2 feedback gain. We used 2k$\Omega$/5k$\Omega$ feedback resistors to obtain accurate gain. We also have to do compensation to guarantee stability. After several trials 50fF of compensation capacitance is found out to be the most proper capacitor value. As always this positive improvement has a negative effect on slew rate of the op-amp, which can only be solved by increasing output stage’s aspect ratio and thus also increasing the output offset.

Although we used feedback we could not reach input range swing because of two obvious problems.

- Clipping of output voltage swing because of the topological behaviour,
- Having soft corners in DC voltage sweep characteristics, which means having lower gain while the input signal becoming near to both supply ranges.

Clipping of output voltage, is solved by further increasing feedback resistor values while keeping the ratio of these two resistors constant, and also increasing the aspect ratio of the output stage’s aspect ratios. But soft corners in the DC characteristics still remain after all these steps have been taken. Soft corners in DC characteristics could only be resolved by increasing the feedback resistor’s value from 50 k$\Omega$ to 75k$\Omega$. We saw that this solution is not enough to reach the supply rails in feedback configuration.
Simulation results of low open-loop gain OTA based op-amp are given in Figure 5.20 to Figure 5.23.

Figure 5.20 DC characteristics of low-open loop gain OTA based op-amp.

Figure 5.21 Open loop AC characteristics of low-open loop gain OTA based op-amp.
Figure 5.22 Closed loop AC characteristics of low-open loop gain OTA based op-amp.

Figure 5.23 Transient response of X2 feedback configuration to a 200 MHz 800 mV<sub>pp</sub> input pulse signal.
<table>
<thead>
<tr>
<th>Input offset</th>
<th>3.80 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output offset</td>
<td>90.18 mV</td>
</tr>
<tr>
<td>$I_B$</td>
<td>50 μA</td>
</tr>
<tr>
<td>Open loop gain</td>
<td>33.4996 dB</td>
</tr>
<tr>
<td>$f_{180}$</td>
<td>1.79369 GHz</td>
</tr>
<tr>
<td>$f_0$</td>
<td>2.4259 GHz</td>
</tr>
<tr>
<td>Closed loop $f_{3dB}$</td>
<td>2.58 GHz</td>
</tr>
<tr>
<td>Slew rate</td>
<td>2.8246 V/ns</td>
</tr>
</tbody>
</table>

Table 5.7-a Simulation results of the most important specifications.

<table>
<thead>
<tr>
<th>Pole frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_1$</td>
<td>106.307 MHz</td>
<td>108.778387 MHz</td>
</tr>
<tr>
<td>$p_2$</td>
<td>679.404 MHz</td>
<td>2.0274027 GHz</td>
</tr>
<tr>
<td>$p_3$</td>
<td></td>
<td>2.762945 GHz</td>
</tr>
<tr>
<td>$p_4$</td>
<td></td>
<td>5.451627 GHz</td>
</tr>
<tr>
<td>$p_5$</td>
<td></td>
<td>11.4516 GHz</td>
</tr>
<tr>
<td>Zero frequency</td>
<td>Simulated</td>
<td>Manually calculated</td>
</tr>
<tr>
<td>$z_1$</td>
<td>679.3941 MHz</td>
<td>1.681914 GHz</td>
</tr>
<tr>
<td>$z_2$</td>
<td></td>
<td>10.903254 GHz</td>
</tr>
</tbody>
</table>

Table 5.7-b Comparison of simulated and manually calculated pole/zero frequencies

In order to achieve real sample-and-hold operation we now have to design an op-amp, which is stable in negative feedback configuration.
5.6 OTA Based Op-amp Designed for Unity Gain Configuration

<table>
<thead>
<tr>
<th></th>
<th>( W (\mu m) )</th>
<th>( L (\mu m) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M1 )</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>( M2 )</td>
<td>2</td>
<td>0.5</td>
</tr>
<tr>
<td>( M3 )</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>( M4 )</td>
<td>0.36</td>
<td>0.18</td>
</tr>
<tr>
<td>( M5 )</td>
<td>0.72</td>
<td>0.18</td>
</tr>
<tr>
<td>( M6 )</td>
<td>0.72</td>
<td>0.18</td>
</tr>
<tr>
<td>( M7 )</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>( M8 )</td>
<td>0.26</td>
<td>0.24</td>
</tr>
<tr>
<td>( M9 )</td>
<td>7.2</td>
<td>0.18</td>
</tr>
<tr>
<td>( M10 )</td>
<td>18</td>
<td>0.18</td>
</tr>
<tr>
<td>( R_f )</td>
<td></td>
<td>75 ( \text{( k\Omega )} )</td>
</tr>
<tr>
<td>( C_f )</td>
<td></td>
<td>50 ( \text{fF} )</td>
</tr>
</tbody>
</table>

Table 5.8 Element aspect ratio’s of unity gain stable OTA based op-amp.

When we simulated low open loop gain configuration as a sample-and-hold configuration we faced a severe problem, because we used resistors in negative feedback, in hold mode of the circuit all charged stored on the hold capacitor during the tracking phase discharged through the feedback resistors to load capacitor immediately. Thus, the output voltage discharges to AC ground in hold mode. There exist three possible solutions to this problem:

- Using the op-amp designed for a feedback gain of 2 in a non-inverting configuration instead of inverting configuration,
- Using a simple source follower at the input of the amplifier,
- Designing a unity gain configuration op-amp to be used as an analog buffer.

We decided to use the third solution because we already have a low open loop gain design which is stable in unity gain configuration. The only problem of this solution is the limited output swing of the topology to be used, approximately \( 1V_{pp} \).
which is already solved by using this configuration in a X2 feedback gain configuration. We only lowered the aspect ratios of both the nMOS and pMOS of the inverter used as the output stage of the op-amp by two, because this op-amp will only have to drive the input stage of the op-amp with low open loop gain, and secondly added a Miller compensation capacitance for a cleaner transient response than the low open loop-gain op-amp. Results are shown in Fig. 5.24 to Fig. 5.26.

**Figure 5.24** DC characteristics of unity gain stable OTA based op-amp.

**Figure 5.25** Open loop AC characteristics of unity gain stable OTA based op-amp.
Figure 5.26 Closed-loop AC characteristics of unity gain stable OTA based op-amp.

Figure 5.27 Transient response of unity gain stable OTA based op-amp to a 200MHz 10 mV_{pp} input pulse signal.
<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input offset</strong></td>
<td>0.399 mV</td>
<td></td>
</tr>
<tr>
<td><strong>Output offset</strong></td>
<td>94.67 mV</td>
<td></td>
</tr>
<tr>
<td><strong>I_B</strong></td>
<td>50 μA</td>
<td></td>
</tr>
<tr>
<td><strong>Open loop gain</strong></td>
<td>33.4855 dB</td>
<td></td>
</tr>
<tr>
<td><strong>f_{180}</strong></td>
<td>2.2597 GHz</td>
<td></td>
</tr>
<tr>
<td><strong>f_0</strong></td>
<td>1.4015 GHz</td>
<td></td>
</tr>
<tr>
<td><strong>Closed loop f_{3dB}</strong></td>
<td>1.43 GHz</td>
<td></td>
</tr>
<tr>
<td><strong>Slew rate</strong></td>
<td>781.63 V/μs</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.9-a Simulation results of the most important specifications.

<table>
<thead>
<tr>
<th>Pole frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>p_1</td>
<td>37.19636 MHz</td>
<td>37.1877 MHz</td>
</tr>
<tr>
<td>p_2</td>
<td>679.4 MHz</td>
<td>2.762944 GHz</td>
</tr>
<tr>
<td>p_3</td>
<td></td>
<td>3.6377 GHz</td>
</tr>
<tr>
<td>p_4</td>
<td></td>
<td>4.451627 GHz</td>
</tr>
<tr>
<td>p_5</td>
<td></td>
<td>6.59124 GHz</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Zero frequency</th>
<th>Simulated</th>
<th>Manually calculated</th>
</tr>
</thead>
<tbody>
<tr>
<td>z_1</td>
<td>679.4 MHz</td>
<td>2.8456 GHz</td>
</tr>
<tr>
<td>z_2</td>
<td></td>
<td>10.9032 GHz</td>
</tr>
</tbody>
</table>

Table 5.9-b Comparison of simulated and manually calculated pole/zero frequencies.

Thus the sample-and-hold circuit and also the residue amplifier to be used in the design is now ready and given in Figure 5.28 and Figure 5.29. Simulation results of this sample-and-hold circuit is given in Figure 5.30 to Figure 5.35. Also simulation results of designed residue amplifier given in Figure 5.29, are given from Figure 5.36 to Figure 5.37.
Figure 5.28 Block representation of sample-and-hold circuit.

Figure 5.29 Block representation of residue amplifier circuit.
Figure 5.30 Sampled voltage versus sampling pedestal, where input signal frequency is 50 kHz and sampling clock frequency is 200MHz.

Figure 5.31 Sampled voltage versus held voltage, where input signal frequency is 50 kHz and sampling clock frequency is 200MHz.
Figure 5.32 Sampled voltage versus settling time, where input signal frequency is 50 kHz and sampling clock frequency is 200MHz.

Figure 5.33 Sampled voltage versus sampling pedestal, where input signal frequency is 30 MHz and sampling clock frequency is 200MHz.
Figure 5.34 Sampled voltage versus held voltage, where input signal frequency is 30 MHz and sampling clock frequency is 200MHz.

Figure 5.35 Sampled voltage versus settling time, where input signal frequency is 30 MHz and sampling clock frequency is 200MHz.
Figure 5.36 Residue voltage obtained versus input voltage for typical simulation corner.

Figure 5.37 Amplified residue voltage by X8 amplification factor in residue amplifier circuit.
Given simulation results for sample-and-hold amplifier clearly states that the designed sample-and-hold amplifier (Fig. 5.28) is not precise enough for a 12bit A/D conversion application because of its sampling pedestal. Thus, an external high-speed, highly precise S&H amplifier has to be used for the characterization of the circuit.

On the other hand simulation results related to residue amplifier circuit are as expected. Thus, configuration given in Figure 5.29 will be used as a X8 feedback amplifier in each analog pipeline stage.

Note that simulated poles/zeros of all op-amps are examined up to 1 GHz frequency range. Thus, it is normal that the simulated and the manually calculated poles/zeros are not totally coincide with each other.
6. DESIGN OF ADC/DAC PIPELINE STAGES

Following a detailed study of the specific building blocks (components) in the previous chapters, the design and verification of a complete 4-bit ADC/DAC pipeline stage will be studied in this chapter. The complete schematic view of the 4-bit pipeline stage is shown in Fig. 6.2. It can be seen that the analog components of the proposed pipeline stage architecture consist of a 4-bit flash A/D converter, a 4-bit charge-scaling D/A converter (MDAC) and a residue amplifier, while the digital components include the 4-bit output encoder, the pipeline register banks, and part of the error correction circuitry (binary adder array). Also a simplified schematic view of a 4-stage pipelined Analog-to-Digital converter is given in Figure 6.1. All sub-blocks of the pipeline A/D converter architecture are included in this simplified view. The digital pipeline with error correction algorithm is given detail in Figure 6.1, where DFF and FA stand for a rising edge data flip-flop and 1-bit full adder circuits respectively. Note that the digital building blocks will be examined in detail in Chapter 7. The operation of the encoder sub-block will be explained in detail in this chapter.
Figure 6.1 Four stage pipelined A/D converter schematic. Al and Bi bits are overflow and underflow bits respectively. They will be explained in detail later in this chapter.

Figure 6.2 Full schematic view of a 4-bit pipeline stage.
6.1 Design of the 4-bit Flash A/D Converter

A resistive voltage divider is used between two reference levels, to generate fifteen voltage references needed for a four bits flash A/D converter. We used two external pins for positive and negative reference voltages, which will provide flexibility on choosing the analog input voltage swing range. Thus, sixteen \(2^{N-1}\) resistors were used in order to create fifteen voltage references between the input voltage signal rails (Figure 6.2). We used 500 \(\Omega\) resistors realized as \(polyn\) resistors for all components of the resistor array. We chose \(polyn\) resistors because of their relatively high parasitic capacitance to ground, which will work as a filter to any fluctuations on the reference voltages due to clock feedthrough during the sampling (conversion) points. We will also use \(salicide\) layer in order to increase the sheet resistance of the \(polyn\) layer in the layout. Creating the layout of these resistors plays a very critical role, because their matching is more important than their absolute value. Thus, dummy resistors were used in the layout in order to prevent any edging effect that can cause mismatch, and also each of the eighteen resistors were drawn in an S-shaped form to save area.

After organizing the reference voltage chain, which is the heart of a flash A/D converter, by a resistive voltage divider we manufactured the comparator chain consisting of fifteen comparators for a four-bit conversion. Improved complementary-input comparators are used as the building block of the pipelined stage. We used thermometer code conversion in our A/D converter, which is the most suitable conversion algorithm in our case due to the available complementary outputs of the comparators. Thus, combining the resistor array, the comparator chain and the thermometer-to-binary encoder completes our 4-bit flash ADC. The simulated DC, time domain transient and frequency domain (AC) characteristics of the 4-bit ADC are presented in the following figures. The DC characteristics (INL and DNL plots) indicate that the comparator chain described above has an effective resolution of at least 10 bits. The operation is highly linear, and the 4-bit ADC is capable of producing a correct output with no missing codes for a very wide input range (between 0.1 V and 1.7 V).
Figure 6.3 DC input-output characteristics of a 4-bit A/D converter.

Figure 6.4 Typical corner DNL plot for 4bit A/D converter.
Figure 6.5 Typical corner INL plot for 4bit A/D converter.

Figure 6.6 Typical FFT plot obtained for a 4-bit A/D converter when the input signal frequency is 10 MHz and the sampling clock frequency is 300 MHz.

To evaluate the dynamic performance of the ADC chain with transistor-level simulation, a sampled sinusoidal signal was applied to the input, and the resulting
thermometer code was converted back into the analog domain for comparison. Note that the sampling of the input signal as well as the digital-to-analog conversion were done using ideal circuit elements, so that the observed differences between the input and the output waveforms can only be attributed to the non-idealities of the 4-bit ADC circuit.

The signal-to-noise ratio (SNR) is calculated from Fourier transformation. The SNR is calculated by measuring the difference between the signal peak and the noise floor. Note that for discrete Fourier transformations, where only a finite number of samples are taken (K samples), the signal energy increases by a factor of $K^2$ while the noise energy increases by a factor of $K$. Therefore the SNR has to be calculated as the difference of the signal peak and the noise floor minus a correction term of $10 \log(K)$.

\[ \text{SNR}(dB) = \text{signal peak}(dB) - \text{noise floor}(dB) - 10 \log(K) \]  

(6.1)

The simulated input and output waveforms, as well as the calculated FFT plot are shown in Figure 6.6 for a signal frequency of 10 MHz and sampling frequency of 300 MHz. Note that the signal peak is at zero “0” dB, the noise floor at -53.405 dB, and number of data samples (K) is 601 in Figure 6.6. Thus the SNR is equal to 25.616 dB, where the theoretical upper limit of the SNR value for a 4-bit A/D converter is 25.84 dB. Figure 6.7 shows the SNR in function of the sampling clock frequency in the case that the input signal frequency is constant at 10 MHz. It can be seen that the signal-to-noise ratio is relatively low for sampling frequencies that are close to the Nyquist limit, and that the SNR approaches the theoretical limit of 25.84 dB as the sampling frequency increases. Figure 6.8 shows the high frequency dynamic performance of the designed 4-bit A/D converter, again with an input signal frequency of 10 MHz. As expected, the SNR decreases gradually for sampling frequency values above 500 MHz, and drops by -3 dB at about 1 GHz. Thus, the dynamic operation of the designed 4-bit ADC is verified to remain within acceptable limits, even for sampling frequencies of up to 1 GHz. Figure 6.9 shows the overall variation of the SNR with the sampling clock frequency, i.e., combining the information provided in Fig. 6.7 and Fig. 6.8. Finally, Figure 6.10 shows the SNR as a function of the input signal frequency in the case of sampling clock frequency held constant at 200 MHz. It can be seen that the SNR gradually drops from its near-ideal level of 25.2 dB at 10 MHz to about 22.7 dB at 80 MHz, as the signal frequency approaches the Nyquist limit of 100 MHz.
In order to achieve analog pipelining we still have to build-up a digital-to-analog converter, DAC. We need a high-resolution, high-speed, monotonic DAC in our work. We searched for different D/A converter topologies in the literature to find the most suitable one for our usage. A brief comparison will be given in the following section.

Figure 6.7 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 50 MHz to 300 MHz.
Figure 6.8 SNR of the 4-bit ADC as a function of sampling frequency, with input signal frequency of 10 MHz and the sampling clock frequency is varied from 500 MHz to 1.2 GHz.

Figure 6.9 Overall variation of SNR as a function of the sampling frequency, with input signal frequency of 10 MHz.
Figure 6.10 SNR of the 4-bit ADC as a function of input signal frequency, with sampling clock frequency of 200 MHz and the input signal frequency is varied from 10 MHz to 80 MHz.

6.2 Digital-to-Analog Converter Design

In general, an A/D conversion process will convert a sampled-and-held analog signal to a digital word that represents the sampled analog signal. The D/A conversion process is essentially the reciprocal of the A/D conversion process. Digital words are applied to the input of the D/A to create from a reference voltage an analog output signal that represents the digital word.

The ideal static behavior of a D/A converter is shown in Figure 6.11. The digital word is on the horizontal axis, which consists of all possible combinations of that word. Figure 6.11 is for a 3-bit digital word. The vertical scale is the analog output of the ideal D/A converter. For each digital word, there should be a unique analog output signal. Any deviations from Figure 6.11 fall into the category of static-conversion errors. These errors can affect the following characteristics: integral linearity, differential linearity, absolute linearity, resolution, zero and full-scale error, and monotonicity. All these
specifications define the accuracy of the converter, its static and dynamic performances. For detailed information on these specifications, please refer to chapter 2 because all specifications defined above are also the same for an A/D converter.

6.2.1 Current weighting D/A converter using ladder networks

There exist different systems using ladder networks to obtain accurate current weighting in the literature. These ladder networks are simple to implement in the integrated circuits. Furthermore, the very well matched value and thermal tracking of components on the same die improve the overall performance of the system. R-2R ladder network, resistor weighting current network, equal currents output ladder network, two-step current division network, binary weighted current divider and MOS ladder network are several examples for current weighting D/A converters.

Because of weighting used, the largest transistor has a size, which is \(2^{N-1}\) times the size of the transistor in the least significant bit. Such a ratio in transistor sizes requires a large die size. Moreover, the output capacitance of the MSB current source is large due to the parallel connection of \(2^{N-1}\) transistors. Such a large capacitance has a drawback on the latency of switching this current on and off to the output terminal. As a result it is difficult to operate all switches at the same speed, which will result in an output glitch.
Using more elements in parallel to generate the high current values, which simultaneously increase power consumption of the converter, increases the weighting accuracy [6].

6.2.2 Self-calibrating D/A converters

The system consists of a main D/A converter and a sub-D/A converter used to eliminate the errors in the main D/A converter. During calibration cycle an analog ramp is generated using a ramp generator. The output of the main D/A converter is compared with the ramp signal by a comparator. The correction logic generates a digital correction signal that is stored in a RAM unit. The RAM data control the sub-D/A converter to correct the output signal of the total D/A converter function to obtain the full \( \frac{1}{2} \) LSB integral nonlinearity. Main disadvantages of this topology are the required number of bits to be stored to correct the main D/A output and the fact that during calibration the D/A converter cannot be used for conversion [6].

6.2.3 Voltage and charge-scaling D/A converters

A very important component of a D/A converter is the accurate scaling of the reference voltage \( V_{\text{REF}} \). The analog output is equal to this scaled value, which is determined by the digital word. Scaling is usually accomplished by the use of passive components, e.g., resistors or capacitors. Resistors are used to accomplish voltage scaling whereas capacitors are used to accomplish charge scaling.

Voltage scaling uses series resistors connected between the positive reference voltage, \( +V_{\text{REF}} \), and negative voltage reference, \( -V_{\text{REF}} \), to obtain voltages between these limits. For an N-bit converter, the resistor string would have at least \( 2^N \) segments. An op-amp can be used to buffer the resistor string from loading effect of the switches used to control the output voltage level. Each tap is connected to a switching tree whose switches are controlled by the bits of the digital word. If the \( ith \) bit is “1”, then the switches controlled by \( b_i \) are closed. If the \( ith \) bit is “0”, then the switches controlled by \( b_i \) are opened (Figure 6.12).

It is seen that the voltage scaling D/A structure is very regular and thus well suited for MOS technology. An advantage of this architecture is that it guarantees monotonicity, for the voltage at each tap cannot be less than the tap below. The area
required for the voltage-scaling D/A converter is large if the number of bits is eight or more. Also, the conversion speed of the converter will be sensitive to parasitic capacitances at each of its internal nodes.

Charge-scaling D/A converters operate by binarily dividing the total charge applied to a capacitor array, or by just equally weighting the total charge applied to a capacitor array. It has been proved that the total number of capacitors in both structures will be $2^N$ (N is the number of bits of the converter). A two-phase nonoverlapping clock is used for this kind of converters. During the $\phi_1$ the top and the bottom plates of all capacitors in the array are grounded. Next, during $\phi_2$, the capacitors associated with bits that are “1” are connected to $+V_{\text{REF}}$ and those with bits that are “0” are connected to $-V_{\text{REF}}$. The output of the D/A converter is valid during $\phi_2$ (Figure 6.13).

The accuracy of the capacitor and the area required are both factors that limit the number of bits used. The accuracy is seen to depend upon the capacitor ratios in the binary weighting charge-scaling DAC and to capacitor mismatch in equally weighting charge-scaling DAC. The ratio error for capacitor in MOS technology can be as low as

![Figure 6.12 Implementation of a 3-bit voltage scaling D/A converter [6].](image)
0.1%. If capacitor ratios were able to have this accuracy, then a D/A converter that is capable of 10-bit resolution could be realizable. However, this implies that the ratio between the MSB and LSB capacitors will be 1024:1 in the extreme case, which is undesirable from an area viewpoint for a binary weighting charge-scaling D/A converter. Also, the 0.1% capacitor ratio accuracy is applicable only for ratios in the neighborhood of unity. As the ratio increases, the capacitor ratio accuracy decreases. But, for an equally weighting charge-scaling D/A converter, the total area can be expressed as $2^N C_{\text{unit}}$, which will result in a more desirable chip area. Moreover, response time of an equally weighting charge-scaling DAC is better than the binary weighting one due to the large capacitance appeared on MSB ($C_{\text{unit}} 2^{N-1}$) because of the binary weighting structure. The working principle of an equally weighting DAC (MDAC) given in Figure 6.13 with only a single clock ($\phi_1$) and its inverse ($\phi_2$) - two phased working principle - instead of two non-overlapping clocks can be expressed as follows:

$$Q_{\text{Precharge}} = \sum C_{\text{UNIT}} (V_r - V_m) \text{inCLK}$$

$$Q_{\text{Evaluation}} = \sum C_{\text{UNIT}} (V_r' - V_{BT}) \text{inCLK}$$

where $V_r' = V_r + \Delta V_r$  \hspace{1cm} (6.2)

Figure 6.13 N-bit charge-scaling D/A converter schematic [6].
From the charge conservation principle these two charges stored on the MDAC.OUT node (Figure 6.11) should be equal to each other: 

\[ Q_{\text{Precharge}} = Q_{\text{Evaluation}} \].

Deriving \( \Delta V_r \) (residue voltage) from this equality results in

\[
\Delta V_r = \frac{1C_{\text{UNIT}}}{2^{N-1}C_{\text{UNIT}}} \sum V_{\text{BIT}} - V_{\text{in}}
\]

(6.3)

The residue voltage formed at the output of MDAC is equal to the difference of the produced analog voltage in DAC and the input analog voltage to the pipeline stage. The value of this voltage is not dependent on the absolute unit capacitor value but on the ratio of the decoder capacitances. The influence of the capacitor ratio accuracy on number of bits of a charge-scaling D/A converter can be shown as follows:

The ideal output voltage of the charge-scaling D/A converter is,

\[
\frac{V_{\text{OUT}}}{V_{\text{ref}}} = \frac{C_{\text{equivalent}}}{NC_{\text{UNIT}}}
\]

(6.4)

Now assume that the worst-case output voltage is given as,

\[
\frac{V_{\text{OUT}}}{V_{\text{ref}}} = \frac{C_{\text{equivalent}} \text{ (min)}}{NC_{\text{UNIT}} - C_{\text{equivalent}} \text{ (max)} + C_{\text{equivalent}} \text{ (min)}}
\]

(6.5)

Then the difference between the ideal output and the worst-case output can be written as,

\[
\left| \frac{V_{\text{OUT}}}{V_{\text{ref}}} - \frac{V_{\text{OUT}}}{V_{\text{ref}}} \right| = \left| \frac{C_{\text{equivalent}}}{NC_{\text{UNIT}}} - \frac{C_{\text{equivalent}} \text{ (min)}}{NC_{\text{UNIT}} - C_{\text{equivalent}} \text{ (max)} + C_{\text{equivalent}} \text{ (min)}} \right|
\]

(6.6)

If we assume the worst-case condition occurs at the midscale, then the \( E_{\text{equivalent}} \) becomes \( N/2C_{\text{unit}} \). Therefore the difference can be expressed as,

149
\[ \left| \frac{V_{\text{out}}}{V_{\text{ref}}} - \frac{V_{\text{out}}}{V_{\text{ref}}} \right| = \frac{N/4 - N/2 C_{\text{UNIT}} \text{ (min)}}{N/2 C_{\text{UNIT}} \text{ (max)} + N/2 C_{\text{UNIT}} \text{ (min)}} \] (6.7)

Replacing \( C_{\text{UNIT}} \text{ (max)} \) by \( C_{\text{UNIT}} + 0.5\Delta C \) and \( C_{\text{UNIT}} \text{ (min)} \) by \( C_{\text{UNIT}} - 0.5\Delta C \) and setting the difference between the ideal and worst-case output voltage equal to \(+0.5\text{LSB}\) results in the following equation

\[ \left| \frac{\Delta C}{C_{\text{UNIT}}} \right| = \frac{1}{2^n} \] (6.8)

Consequently, as a result of this topology survey we decided to use an equal weight "Multiplying Digital-to-Analog Converter" (MDAC) in our pipeline stage. We preferred this topology because it is the most suitable one for our case regarding speed, power consumption, area, and linearity. We preferred using unit capacitors to be used for charge-scaling at the output of each fifteen comparators because we will use directly the thermometer code and its complement created at the falling edge of \( \phi_1 \). Moreover, the subtraction process needed between the held input analog voltage and the reconstructed analog voltage by the DAC to achieve analog pipelining between two consequent pipeline stages can be done without any extra design steps. This voltage difference is named the residue voltage of the pipeline stage. This subtraction process is achieved by the help of two extra CMOS switches that simply connect the top plates of all capacitors in the array to analog input voltage instead of ground and bottom plates to a fixed reference voltage in \( \phi_1 \) as given in Figure 6.14 [3].

The most challenging step in the design of an MDAC is to find the appropriate sizes of the complementary MOS switches that will result in low clock feedthrough, low series resistance, and high output driving capability. The later two specifications require wide MOS switches, while the first one requires narrow widths. Thus, simulations were done on the sizing of CMOS switches to identify the acceptable minimum width needed for the switch transistors. Consequently, aspect ratio of 5\( \mu \text{m}/0.18\mu \text{m} \) is used for all switches in the design.
Figure 6.14 Schematic view of a 4 bit MDAC.

Another important point in a charge-scaling D/A converter design is the identification of the value of the minimum acceptable unit capacitor. A unit capacitor of 50 fF is used in the design that provides needed speed and linearity specifications. Each unit capacitor can only be implemented as metal-metal capacitors due to the technology limitations. Thus, layouting this capacitance array is a great deal to be achieved. As mentioned before matching of these fifteen capacitors is more critical than their absolute value. Hence, we could say that matched capacitors form the basis of most data conversion products such as analog-to-digital and digital-to-analog converters. We can classify matching in three groups listed as follows:

- Minimal matching: Approximately ±1% three-sigma mismatch, or 6 to 7 bits of resolution.
- Moderate matching: Approximately ±0.1% three-sigma mismatch, or 9 to 10 bits of resolution.
- Precise matching: Approximately ±0.01% three-sigma mismatch, or 13 to 14 bits of resolution. Suitable for precision A/D and D/A converters.
Precisely matched capacitors usually employ a thick oxide dielectric in conjunction with deposited electrodes. Junction capacitors have difficulty maintaining even minimal matching due to their extreme temperature dependence and the effects of out-diffusion. The following hints summarize the most important principles of constructing matched deposited-electrode capacitors.

- Use identical geometries for matched capacitors. Capacitors of different sizes or shapes match poorly; so matched capacitors should always use identical geometries. Unit capacitors should not be connected in series because differences between the parasitic capacitances of the upper and the lower plates will produce systematic mismatch.

- Use square geometries for precisely matched capacitors. Peripheral variations are a major source of random mismatch in capacitors. The smaller the periphery-to-area ratio, the higher the obtainable degree of matching. The square has the lowest periphery-to-area ratio of any rectangular geometry and therefore yields the best matching. Rectangular capacitors with moderate aspect ratios (2:1 or 3:1) can be used to construct moderately matched capacitors, but precisely matched capacitors should always be square. In reality, the value of an integrated capacitor is not equal to the product of the specific capacitance \( \frac{C_o}{d} \) of the designed area of the plate. The etching that defines the plate proceeds under the protective mask (undercut effect) and reduces the designed area:

\[
A_{\text{eff}} = (W - 2x)(L - 2x) \approx WL - 2(W + L)x = A - Px
\]  

(6.9)

where \( A \) is the designed area and \( P \) is the perimeter. Thus, the effective area is smaller than the designed area by an amount proportional to the perimeter of the plate. Thus, in order to also match the reduction effect due to undercut, it is necessary to keep the area-perimeter ratio as small as possible.

- Make matched capacitors as large as practical. Increasing the size of capacitors reduces random mismatch as well as dividing large capacitors into practical sized parts, which will introduce cross coupling that will minimize gradient effects and improve overall matching.
Place matched capacitors adjacent to one another. If large number of capacitors is involved, they should be arranged to form a rectangular array having a small aspect ratio as possible. Adjacent rows of unit capacitors should have equal spacing between them, as should adjacent columns of unit capacitors.

Place matched capacitors over field oxide. Matched capacitors should always reside over field oxide well away from the edges of moat regions and diffusions.

Connect the upper electrode of a matched capacitor to the higher-impedance node, because this generally exhibits less parasitic capacitance than the lower electrode. If substrate noise coupling is a concern, consider placing a well under the entire array.

Place dummy capacitors around the outer edge of the array. Both electrodes of each dummy capacitor must be connected to prevent static charges from accumulating on the dummy electrodes and interfering the operation of adjacent devices.

Electrostatically shield the capacitor array. Electrostatic shielding provides several benefits. First, it contains fringing fields to the capacitor array, thereby eliminating the need for wide arrays of dummy capacitors. Second, it allows leads to route over the capacitors without causing mismatch or noise injection. Third, it prevents electrostatic fields from adjacent circuitry from interfering with the matched capacitors. Fourth, it reduces the effects packaging stress on the underlying capacitors. All precisely matched capacitors should be electrostatically shielded, and this shielding should extend over the dummies placed around matched capacitor array.

Cross-coupled array capacitors preferred. Cross coupling minimizes the effects of oxide gradients on capacitor matching and provides protection against stress and thermal gradients.

Consider the number of the leads connected to the matched capacitor.

Do not run leads over matched capacitors unless they are electrostatically shielded.

Use thick-oxide dielectrics in preference to thin-oxide or composite dielectrics.
If possible, place capacitors in areas of low stress gradients. The stress distribution reaches a broad minimum in the middle of the die.

Place matched capacitors well away from power devices.

Place precisely matched capacitors on axes of symmetry of the die [16].

Concerning all the explained properties of the capacitor array that will be used in the multiplying D/A converter and all the hints given above to help the designer to be able to layout matched capacitor arrays we decided to draw the sixteen unit capacitors as square shapes in a common-centroid form, and also in order to be able to reduce the occupied area by each unit capacitor we draw each unit capacitance in fractals. Hence, every fringe capacitor value will also be added to the total capacitance value. What is more, we will place this capacitor array in an N-well in order to be able to shield the array from the substrate noise. We also draw each unit capacitor as a sandwich made up of consequent metal layers (up to metal 5) connected in series (Figure 6.15). Thus, in order to construct 50 fF of unit capacitors we will consume less area than the area of a single sheet capacitor. Reduction in the area will further increase matching between array elements.

![Diagram](image)

**Figure 6.15** Simplified cross-section representation of metal-metal capacitors constructed in N-well. Note that N-well is not shown in figure for simplicity.

The ADC/MDAC structure that was described here takes the held analog input voltage, compares it with the reference voltages created by a resistor divider through the
comparators and reconstructs the digitally represented analog signal via the MDAC into analog format again. Then, we subtract that reconstructed analog signal from the held input voltage. Now the residue voltage is ready at the output of the D/A converter. If not any unpredictable conversion error arises, by definition this residue voltage must not be bigger than |−100mV| in our 4-bit A/D converter. In order to achieve pipelining now we have to amplify this residue voltage to full scale by the help of a residue amplifier. Note that, the full scale for the pipeline stages following the first stage should be half the input swing range of the first stage in the A/D converter. This is needed because we will use bit-overlapping technique in the digital pipeline in order to be able to correct any conversion error that can arise in the preceding stage. Thus, an op-amp with a closed loop gain of X8 is needed as the residue amplifier. The high open loop-gain OTA based op-amp will be used in negative feedback configuration (Figure 5.29). The residue voltage formed on the unit capacitors of the MDAC will be rapidly sinked to ground through the feedback resistors and the output stage of the op-amp, which is the same problem faced with the sample-and-hold amplifier. Thus, the same solution will be applied here. A unity gain OTA based op-amp designed (refer to chapter 5) will be placed in between the DAC output and the series feedback resistor. Consequently only a MOS transistor’s gate will be seen by the DAC output thus, no charge will be lost (Figure 5.29). The amplified residue voltage at the output of the residue amplifier will be used as the held input voltage by the proceeding pipeline stage. In order to hold this amplified residue voltage constant during the sensing phase of the comparators of the proceeding stage a sample-and-hold circuit must be introduced. What is more, as explained before, the algorithm used in a MDAC being charge-scaling, any voltage changes on the top plate of the unit capacitor will be reflected directly to the D/A converter’s output. In order to prevent this phenomenon and to be able to hold the amplified residue constant during the conversion phase of the proceeding stage, we buffered the comparator outputs of the flash A/D converter via the sampling clock. Thus, the comparators will keep their previous state up to the next decision time. In other words sensing the phase of the comparators will be invisible to MDAC capacitors. Thus, the residue voltage will be constant for a half period of sampling clock, and the same is true for the amplified residue voltage. Simulated residue and amplified residue voltages are given respectively in Figure 6.16 and Figure 6.17 for typical corner silicon Spice parameters. Also, the variation of these two voltages with respect to the analog signal applied at the input of the pipeline stage is provided in Figures 6.18 and 6.19. It
can be seen that the amplified residue signal has the expected saw-tooth shape that corresponds to the difference between the analog input level and the quantized output levels. The transitions are perfectly linear, the amplitude of the signal is 800 mV (with a maximum error of ± 4.7 mV) and the amplified residue signal remains within (± 10 mV) of the ideal upper and lower boundaries, i.e. 0.5 V and 1.3 V, respectively. With these properties, it can be verified that each pipeline stage is capable of producing the output bits with the desired accuracy.

In Figures 6.20 and Figure 6.21, the time-dependent variation of the residue voltage and the amplified residue voltage are given for a sampling clock frequency of 50 MHz, respectively. Note that the residue voltage and the amplified residue voltage have more time to settle until the next falling edge of the clock signal arrives, and consequently, the accuracy of the pipeline stage response is expected to increase at lower sampling frequencies. The exact variation of the residue voltage as a function of the input voltage level was not produced at 50 MHz, since the results obtained for 200 MHz sampling frequency are already quite adequate for the desired bit-precision.

Figure 6.16 Residue voltages obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 200 MHz.
Figure 6.17 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 200 MHz.

Figure 6.18 Residue voltage obtained versus input voltage for typical simulation corner at 200 MHz sampling rate.
Figure 6.19 Variation of the amplified residue voltage given in Figure 6.19 as a function of the input voltage level, with X8 amplification factor.

Figure 6.20 Residue voltages obtained for different input voltage levels applied to the input of the 4-bit pipeline stage. The sampling clock frequency is 50 MHz.
Figure 6.21 Time-dependent variation of the amplified residue voltage, with a sampling clock frequency of 50 MHz.

6.3 Error Correction with Bit-Overlapping

As mentioned before we decided to use “bit-overlapping” technique to achieve error correction. We choose this architecture because of its simplicity. In order to be able to use this technique we have to design more precise comparators to be used in the pipeline stages that follow the first one. We used “single bit-overlapping” technique thus; we had to decrease the input signal swing to one half of its original in the proceeding pipeline stages. This phenomena is established by amplifying the residue voltage produced in the preceding stage by “8”, which will result in a halved input signal swing of 800 mV<sub>pp</sub>, where the original input voltage swing is 1.6 V<sub>pp</sub>. Thus, the amplified residue voltage will be 800 mV<sub>pp</sub> with a DC offset of 0.9V. Up to this point no error correction is done. Coding errors will arise if the previous stage’s residue signal is greater than 1LSB. Causes of this kind of errors were examined in Chapter 2. Error correction is introduced in digital pipeline by designing a clever encoder (Figure 6.22) that can distinguish the possible over / under flow states from the decoded 4bits of the
related pipeline stage (pipeline stages 2, 3 and 4). The encoding technique used in these stages is explained in detail in Table 6.1. For example, if the amplified residue of the first stage is greater than 1.3 volts an over flow state occurs. The following analog pipeline stage will produce the thermometer code representing this analog input voltage, and an over-flow flag \((A = 1)\) will be produced by the 12th comparator’s “Q” output as the 4th MSB bit of the related pipeline stage in the clever encoder circuit. This raised over-flow flag will be added to the preceding pipeline stage’s output and the rest of the digital word produced (3bits), will be concatenated to the resulting digital code (Figure 6.23). If the amplified residue of the first stage is less than 0.5 volts an under flow state is occurred. The following analog pipeline stage will produce the thermometer code representing this analog input voltage, and an under flow flag \((B = 1)\) will be produced by the 4th comparator’s “\(\bar{Q}\)” output as the 4th MSB bit of the related pipeline stage in the clever encoder circuit. This raised under-flow flag will be subtracted from the preceding pipeline stage’s output and the rest of the digital word produced (3bits), will be concatenated to the resulting digital code (Figure 6.23). And if the amplified residue of the stage is in between the 0.5V-1.3V range than “0” will be added to the following stage’s 4-bit output and produced 3-bits will be concatenated to the resulting digital code (Figure 6.23).

Figure 6.22 Simplified schematic view of a 4-bit encoder block used in stage 1.
Figure 6.23 *Bit-overlapping* technique that is used in the design of the pipeline stages.
<table>
<thead>
<tr>
<th>Decimal representation of the thermometer code</th>
<th>Binary code produced in STAGE 1 Encoder</th>
<th>Binary code produced in STAGES 2, 3 and 4 Encoders</th>
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<tr>
<td>15</td>
<td>1111</td>
<td>011</td>
</tr>
<tr>
<td>14</td>
<td>1110</td>
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<tr>
<td>0</td>
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</table>

Table 6.1 Encoding strategy of the related pipeline stage.

Note that over / under flow flags are not given in Table 6.1. They simply correspond to the 4th and the 12th comparator outputs. Also note that 3-bit codes are highlighted for pipeline stages 2, 3 and 4 in over / under flow states.

Design and verification of a full 4bit analog pipeline stage is completed by combining all the building blocks together. In order to achieve 4-stage pipelining we now have to design the digital pipeline’s building blocks, such as data flip-flops, full adders, OR and XOR gates and buffers. Design and verification of these digital blocks will be examined in detail in Chapter 7.
7. DESIGN OF DIGITAL BUILDING BLOCKS

Following the design of the analog pipeline components, we now turn our attention to the digital building blocks that are needed to establish full pipeline operation. More specifically, we will have to design the 11-bit adder to construct the output word, the 4-bit thermometer-to-binary encoder that is constructed by XOR gates, buffers, and finally data flip-flops to establish pipelining at the rising edge of the sampling clock. Design and verification of these digital pipeline stage elements will be examined in this chapter.

7.1 Full Adder Design

Addition forms the basis for many important binary operations from counting to multiplication to filtering. As a result, adder circuits that add two binary numbers are of great interest to digital system designs. A wide variety of adder implementations are available to serve different speed/density requirements. Considering the Boolean description of the binary adder circuit, let A and B the two binary input variables (addend bits), and let C the represent the carry_in bit. The binary full adder is a three-input, two-output combinational circuit that satisfies the truth table given in Table 7.1.
<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>sum_out</th>
<th>carry_out</th>
</tr>
</thead>
<tbody>
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<td>0</td>
<td>0</td>
</tr>
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<td>1</td>
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<td>1</td>
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<td>1</td>
<td>0</td>
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<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.1 Truth table for the full adder circuit.

A and B are the adder inputs, C is the carry input, sum_out is the sum output, and carry_out is the carry output.

### 7.1.1 Single-bit adders

Probably the simplest approach to design an adder is to implement gates to yield the required majority logic functions. The sum_out and the carry_out signals can be found as the following two combinational Boolean functions of the three input variables, A, B and C. From the truth table these are:

\[
\begin{align*}
\text{sum}_\text{out} &= A \oplus B \oplus C \\
&= ABC + AB\overline{C} + \overline{ABC} + \overline{ACB} \\
\text{carry}_\text{out} &= AB + AC + BC
\end{align*}
\]  

(7.1)

which may be factored as follows:

\[
\begin{align*}
\text{sum}_\text{out} &= C\left(AB + \overline{AB}\right) + \overline{C}\left(\overline{AB} + \overline{AB}\right) \\
\text{carry}_\text{out} &= AB + C(A + B)
\end{align*}
\]  

(7.2)
Figure 7.1 Gate-level schematic of the one-bit full-adder circuit [10].

The direct gate level realization of these two functions of Eq. 7.2 is shown in Figure 7.1. Note that instead of realizing the two functions independently, we use the carry_out signal to generate the sum output with an implementation that does not use XOR gates is shown in Figure 7.2. This uses an alternative implementation that is achieved by realizing that the carry_out term reused in the sum_out term as a common subexpression. In this implementation, shown in Figure 7.2, sum_out can be expressed as

\[
\text{sum_out} = ABC + (A + B + C)\overline{\text{carry_out}}
\]

\[
= ABC + (A + B + C)(AB + C(A + B))
\]  

(7.3)

Note that the circuit implementation shown in Fig. 7.2 also makes use of the fact that both functions are symmetric Boolean functions, resulting in identical nMOS and pMOS network topologies.
Figure 7.2 Completely symmetric 1-bit full adder cell [10].

The designed full adder circuit is now simulated in order to determine its dynamic performance. Assuming that the outputs of this adder circuit may drive a similar circuit, both output nodes are loaded with capacitors, which represent the typical input capacitance of a full adder. The three input waveforms (A, B and C) are chosen so that all of the eight possible input combinations are applied consecutively to the full adder circuit. Figure 7.3 shows the simulated input and output waveforms of the full adder circuit.

![Waveform Diagrams]

Figure 7.3 Simulated input and output waveforms of the 1-bit full adder circuit.
7.1.2 Bit-parallel adder

Figure 7.4 Block diagram of a carry ripple adder chain consisting of n 1-bit full adders.

An n-bit adder may be constructed by cascading n 1-bit adders, as shown in Figure 7.4. This implementation is called a Ripple Carry adder. The inputs are n-bit A and B values. The carry_out signal of stage i is fed to the C signal of stage i + 1 and the sum_out signal forms the n-bit output. The nth bit of the sum_out indicates the sign of the result, while the nth carry_out signal indicates whether an overflow condition has occurred. Because the carry-output signal (carry_out) is used in the generation of sum_out in the circuit shown in Figure 7.4, sum_out will be delayed with respect to carry_out. In the case of n-bit parallel adder, the carry delay has to be minimized, because the delay associated with the adder is \( T_n = nT_C \), where \( T_n \) is the total add time, \( n \) is the number of stages, and \( T_C \) is the delay of one carry stage.

We designed a 10-bit ripple carry adder chain described as in Figure 7.4, and simulated the dynamic performance of the chain at 200 MHz. Related simulation results of 10-bit full adder chain are given in Table 7.2 and Table 7.3. Rise and fall time characteristics of carry_out signal are given with the propagation delay of both rising/falling edge of the same signal due to the incoming carry signal in Table 7.2. Also rise and fall time characteristics of sum_out signal are given with the propagation delay of both rising/falling edge of the same signal due to the incoming carry signal in Table 7.3. All results given in these tables are in ps units.
<table>
<thead>
<tr>
<th>carry_out</th>
<th>Rise Time (ps)</th>
<th>Fall Time (ps)</th>
<th>Rising edge PD (ps)</th>
<th>Falling edge PD (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>152</td>
<td>117.69</td>
<td>178</td>
<td>175</td>
</tr>
<tr>
<td>2</td>
<td>152.93</td>
<td>117.53</td>
<td>372</td>
<td>361</td>
</tr>
<tr>
<td>3</td>
<td>152.93</td>
<td>117.52</td>
<td>566</td>
<td>547</td>
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<tr>
<td>4</td>
<td>152.93</td>
<td>117.52</td>
<td>763</td>
<td>733</td>
</tr>
<tr>
<td>5</td>
<td>152.93</td>
<td>117.51</td>
<td>957</td>
<td>920</td>
</tr>
<tr>
<td>6</td>
<td>152.93</td>
<td>117.52</td>
<td>1150</td>
<td>1110</td>
</tr>
<tr>
<td>7</td>
<td>152.93</td>
<td>117.51</td>
<td>1350</td>
<td>1290</td>
</tr>
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<td>117.51</td>
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<td>1480</td>
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<td>9</td>
<td>152.91</td>
<td>117.51</td>
<td>1740</td>
<td>1660</td>
</tr>
<tr>
<td>10</td>
<td>152.91</td>
<td>117.52</td>
<td>1880</td>
<td>1810</td>
</tr>
</tbody>
</table>

Table 7.2 Simulated carry_out dynamic performance results.

<table>
<thead>
<tr>
<th>sum_out</th>
<th>Rise Time (ps)</th>
<th>Fall Time (ps)</th>
<th>Rising edge PD (ps)</th>
<th>Falling edge PD (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>109.57</td>
<td>217.63</td>
<td>343.68</td>
<td>419.07</td>
</tr>
<tr>
<td>2</td>
<td>109.58</td>
<td>217.68</td>
<td>530.18</td>
<td>613.76</td>
</tr>
<tr>
<td>3</td>
<td>109.57</td>
<td>217.68</td>
<td>716.63</td>
<td>808.45</td>
</tr>
<tr>
<td>4</td>
<td>109.58</td>
<td>217.69</td>
<td>903.09</td>
<td>1003</td>
</tr>
<tr>
<td>5</td>
<td>109.57</td>
<td>217.69</td>
<td>1089</td>
<td>1197</td>
</tr>
<tr>
<td>6</td>
<td>109.57</td>
<td>217.7</td>
<td>1275</td>
<td>1392</td>
</tr>
<tr>
<td>7</td>
<td>109.57</td>
<td>217.71</td>
<td>1462</td>
<td>1587</td>
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<td>9</td>
<td>109.57</td>
<td>217.72</td>
<td>1835</td>
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<tr>
<td>10</td>
<td>109.1</td>
<td>217.41</td>
<td>2023</td>
<td>2173</td>
</tr>
</tbody>
</table>

Table 7.3 Simulated sum_out dynamic performance results.

Note that, sum_out is delayed with respect to carry_out signal and what is more carry_out delay increases with increasing the number of bits to be added. Hence, these simulated results states that the dynamic performance of the designed 10-bit ripple carry
adder is suitable for applications at 200 MHz signal frequency. Layout of 1-bit full adder circuit is given in Figure 7.5. The silicon area is approximately 107 µm².

Figure 7.5 Layout view of the designed 1-bit full adder circuit.

7.2 D-type Flip-Flop (DFF) Design

Figure 7.6 CMOS implementation of the D-latch circuit [10].
Figure 7.6 shows the CMOS implementation of D-latch. The circuit contains two tristate inverters, driven by the clock and its inverse. The first tristate inverter acts as the input switch, accepting the input signal when the clock is low. At this time, the second tristate inverter is at its high-impedance state, and the output \( Q \) is following the input signal. When the clock goes high, the input buffer becomes inactive, and the second tristate inverter completes the two-inverter loop, which preserves its state until the next clock pulse.

Figure 7.7 CMOS rising edge-triggered master-slave D flip-flop (DFF) [10].
Now, consider the two-stage master-slave flip-flop shown in Figure 7.7, which is constructed by simply cascading two D-latch circuits given in Figure 7.6. The first stage (master) is driven by the inverse of the clock signal, while the second (slave) is driven by the clock signal itself. Thus, the master stage is negative level-sensitive, while the slave stage is positive level-sensitive.

When the clock signal is low, the master stage flows the DATA input while the slave stage holds the previous state. When the clock changes from logic “0” to “1”, the master latch ceases to sample the input and stores the DATA value at the time of the clock transition. At the same time, the slave latch becomes transparent, passing the stored master value $Q_1$ to the output of the slave stage, $Q$. The input cannot affect the output because the master stage is disconnected from the DATA input. When the clock changes again from “1” to “0”, the slave latch locks in the master latch output and the master stage starts sampling the input again. Thus, this circuit is a positive edge-triggered D flip-flop by virtue of the fact that it samples the input at the rising edge of the clock pulse. Finally we added reset signal to the DFF circuit given in Figure 7.7 by simply adding two extra nMOS transistors to the master stage outputs in such a way that $Q1$ output will be “0” when RESET signal is HIGH. Figure 7.8 shows the simulated input and output waveforms of the two-stage master-slave D flip-flop designed with reset.

Figure 7.8 Simulated input and output waveforms of the CMOS DFF circuit given in Figure 7.7.
The dynamic performance of the designed two-stage master-slave DFF with reset is characterised in three different conditions. Set-up and hold times, most critical attributes of D-type flip-flops, are simulated at 200 mHz clock frequency while the delay between clock and its inverse is 50 ps, 100 ps and 150 ps. The outputs of this DFF circuit are loaded with the same circuit itself. Typical corner simulation results obtained are given in Table 7.4 in ps time unit. Layout view of designed DFF is given in Figure 7.9.

<table>
<thead>
<tr>
<th>Inversion delay (ps)</th>
<th>Set-up (ps)</th>
<th>Rising edge Propagation Delay (ps)</th>
<th>Falling edge Propagation Delay (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>182.5</td>
<td>172.62 ps</td>
<td>141.89 ps</td>
</tr>
<tr>
<td>100</td>
<td>239</td>
<td>177.58 ps</td>
<td>92.179 ps</td>
</tr>
<tr>
<td>150</td>
<td>294.5</td>
<td>180.28 ps</td>
<td>42.8 ps</td>
</tr>
</tbody>
</table>

Table 7.4 Simulated dynamic characteristics of two-stage master-slave DFF circuit.

Figure 7.9 Layout view of the designed D-type flip-flop. Area is approximately 132 µm².
7.3 Exclusive OR Gate Design

The truth table of exclusive OR (XOR) function is given in Table 7.5. The Boolean expression obtained from this truth table is given in Eq. 7.5 and gate level, full CMOS implementation of Eq. 7.5 is given in Figure 7.10 and Figure 7.11 respectively. Note that two extra inverters are needed in Figure 7.11.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>Z</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
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</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7.5 Truth table of exclusive OR function.

\[
Z = A \oplus B \\
= \overline{AB} + \overline{A}B
\]  

(7.5)

Figure 7.10 Gate level representation of XOR function [8].
Figure 7.11 Full CMOS implementation of XOR function [8].

Finally, the designed XOR circuit is simulated in order to verify its dynamic performance while loaded with 5 fF capacitance, which is equivalent to the input capacitance of minimum sized buffer. Typical simulation corner results are given in Table 7.6 and layout view of XOR circuit is available in Figure 7.12. Simulated input and output waveforms at 200 MHz signal frequency are given in Figure 7.13.

| Rising edge Propagation Delay | 51.67 ps |
| Falling edge Propagation Delay | 46.64 ps |
| Rise Time | 137.88 ps |
| Fall Time | 81.48 ps |

Table 7.6 Simulated dynamic performance characteristics of XOR circuit.
Simulated results of the designed 4-bit encoder circuit using XOR gates and buffers (Figure 7.14) are as follows:

- Propagation delay: 443.41 ps
- Rise time: 72.37 ps
- Fall Time: 68.94 ps

Note that, these simulation results are for typical simulation corner.

Figure 7.13 Simulated input and output waveforms of the designed XOR circuit.
Figure 7.14 Simplified schematic view of a 4-bit encoder block.

Note that, other digital blocks designed for this dissertation, such as OR2 gate, buffers and inverters are not explained in detail because of the simplicity of the structures. Design criteria for these cells were speed and almost symmetrical rise and fall times.
8. TOP-LEVEL CONSTRUCTION OF THE PIPELINED ADC

The previous chapters have presented the design of all sub-blocks that are used in the pipelined ADC structure, as well as the complete design of the 4-bit analog pipeline stage and the digital pipeline stage elements. The operation and the performance characteristics of these essential components were also verified with extensive simulations. It was demonstrated that the electrical performance of the sub-blocks are well within the expected bounds so that the operation of the overall ADC architecture can be guaranteed to match the initial specifications. At this point, the final task is to combine the designed components into the final 12-bit pipelined ADC structure, using four cascaded pipeline stages.

8.1. Overall Structure of the Pipeline

A simplified view of the overall ADC architecture is shown in Fig. 8.1, where each analog pipeline component and the corresponding digital outputs are highlighted for better description. It can be seen that the structure consist of four 4-bit flash ADCs, three 4-bit multiplying DACs (MDACs) including their respective residue amplifiers, four thermometer-to-binary code encoders, three adder chains to construct the corrected output word at the end of each conversion step, and the DFFs to facilitate the pipeline.
Figure 8.1 Block level representation of four-stage pipelined A/D converter.

Figure 8.2 Four-stage pipelined ADC clocking scheme.
Figure 8.3 Block level representation of the proposed clock distribution between functional modules of the pipelined ADC architecture.

According to the pipelined operation principle of this four-stage structure, each four-bit stage is capable of processing subsequent portions of four different sampled input signals at any given clock cycle. The processed results are passed on to the following pipeline stage in the next clock cycle, so that the final stage produces a complete 12-bit result (13 bits with overflow) at the end of each clock period. The latency of this pipeline structure is four clock cycles; i.e. the complete conversion of any sampled signal is obtained at the end of the fourth clock period following the sampling edge. Assuming that the clock frequency is set to 200 MHz (as proven to be feasible by previous simulation results) the proposed pipelined architecture is thus capable of generating a 12-bit analog-to-digital conversion every 5 ns.

8.2. Timing Considerations

The simplified clocking scheme of the pipeline architecture is shown in Fig. 8.2. Track and hold phases of the clock are indicated as “T” and “H” respectively. The tracked input analog signal is sampled with the falling edge of the clock and the corresponding 4-bit thermometric code is ready at the output of the 1st pipeline stage’s output with a small time delay. In other words, the output of 1st stage’s flash ADC is
ready at the falling edge of first clock cycle. The encoding process starts right after the
thermometric code is generated, during the following half period in the related encoder
circuit. Meanwhile, the second stage’s input analog signal is constructed by the
multiplying DAC. With the rising edge of the CLK, decoded 1st stage’s 4-bit code
(MSB) by the 1st stage encoder is sampled via the DFFs and held constant until the next
rising edge of the sampling clock. Subsequently, the tracking phase of 2nd pipeline stage
is entered. Thus, the second stage’s flash ADC receives the reconstructed analog signal
at the output of the 1st stage’s MDAC during the next half period. At the end of this half
period (with the falling edge of the clock) the thermometric code representing the
reconstructed analog input signal via the 1st stage MDAC is formed at the output of the
second stage’s flash ADC. Right after the production of the thermometric code by
second stage flash A/D converter, the thermometric to binary code encoding starts. At
the same time the analog-to-digital conversion process takes place at the second stage
MDAC. Meanwhile, a new analog input signal is being processed in the 1st stage, which
is the basis of pipeline operation. The 2nd stage DFFs sample the summation of encoded
1st stage encoder output and the over/under flow bit of the 2nd stage with the rising edge
of the third clock cycle. Similarly, the third stage flash A/D converter receives the
reconstructed analog signal by the second stage MDAC and 15-bit thermometric code
representing this analog signal is ready at the falling edge of 3rd clock cycle. This 15-bit
thermometric code is encoded into a 4-bit binary code in the 3rd stage encoder and also
processed in the 3rd stage MDAC. Summation of the encoded 4-bit binary code and the
2nd stage’s DFF outputs are sampled via the 3rd stage DFFs, held constant until the next
comming rising edge of the clock. Consequently, 4th (last) pipeline stage’s flash A/D
converter operates on the finally reconstructed analog signal. With the falling edge of the
4th clock cycle the thermometric code is formed at the output of the 4th stage’s flash
ADC. Similarly the 4-bit binary code (LSB) is encoded in the 4th stage encoder during
the proceeding half period. Note that no digital-to-analog conversion process takes place
in the last stage. Thus, with the rising edge of the fifth clock pulse the valid 12-bit
digital word that represents the held analog input signal four clock cycles before is
formed at the output of pipelined A/D converter. Thus the latency of the designed
analog-to-digital converter is four clock cycles (20 ns).

Note that the entire analog and digital pipeline structure is designed to operate
with only one clock signal (and its inverse), which is a very significant advantage of the
proposed ADC architecture. As opposed to relying on several clock signals that need to
be generated and distributed with high precision, the sufficiency of a single clock is one of the key factors that make this architecture a very good candidate for modular expansion and simple technology migration. Still, it is highly important to distribute this single clock signal throughout the chip without any clock skew so that the corresponding pipeline stages can operate correctly. Thus, the overall floor planning, layout and clock/signal distribution throughout the system will be important issues that need to be addressed.

8.3. General Floor-planning and Layout Considerations

The totally symmetric appearance of the pipeline ADC makes it easy to repeat the modular building blocks. Hence, as soon as the layout of one pipeline stage is completed, four stage pipeline A/D converter can be constructed very easily and quickly, just by repeating the modules one after another and connecting them in a suitable way.

As already mentioned before, the designed 4-stage 12-bit pipelined A/D converter operates with only one clock and it’s inverse. It is essential to distribute this single clock without any skew throughout the pipeline stages in order to be able to process all the stages accordingly. Thus, we will use clock-tree buffers that are placed symmetrically throughout the chip to distribute the system clock to all stages without any skew. We decided to use five clock-tree buffers placed as follows: The system clock is being fed from outside of the chip with a high drive capable clock-tree buffer (CTBUFX32, numbered as CT1 in Figure 8.3) exactly at the middle of the four pipeline stages, as shown in Figure 8.3. We had to use metal wires as wide as possible in order to reduce the side effects of narrow metal strips such as, high series resistance that can cause voltage drops or fringe capacitors that cause cross-coupling. Thus we decided to route the clock lines throughout the chip using 5 µm wide metal-5 tracks. We chose metal-5 level because of its relatively low parasitic capacitance to substrate that results in considerably low coupling. The disadvantage of this decision is the series resistance of the needed stack “vias” in order to electrically connect the transistors to the clock signal routed on metal-5 tracks. Thus, we used “n × n” via sets all over the chip, where the minimum number of “n” is at least two, which will in return reduce the series resistance, as well as increase the quality of the electrically connectivity. The output of this high drive capable clock-tree buffer (CT1) drives eight clock-tree buffers such as
CTBUFFx16, which have less drive capability than CT1. Each of these second level clock-tree buffers, placed totally symmetrical with respect to the center of the chip drives one of the analog or digital pipeline stages, as shown in Figure 8.3. What is more we short circuit the outputs of these second level clock-tree buffers in the hierarchy, in order to be safe from any possible clock skew that could arise because of any unpredictable signal delay. We use local inverter circuits for the inverse of the clock signal, \( \left( \overline{CLK} \right) \), throughout the chip. We chose this technique because the inverter delays play the dominant role on the efficiency of the sub-blocks rather than the skew.

What is more we use a lattice shaped routing for ground (GND), clock (CLK) and supply (VDD) signals on metal levels 4, 5, and 6 respectively as shown in Figure 8.4 throughout the chip. We use 5 µm wide metal tracks for all three level metals and construct a network from this lattice shape as given in Figure 8.5. Thus we use metal-2 or metal-3 (if needed) for lower hierarchy routing between pipeline stages. Note that metal-1 level is used for routing within the sub-block layouts. It is also important to note that we have to reconstruct this latticework over multiplying D/A converter areas because we used all the metal levels in order to construct the unit capacitors and their shielding. Thus, special care must be taken over these areas in the top-level floor planning.

Up to now we finished the design of each sub-block layout, taking special care to make them modular. Also we described the signal routing strategy in detail in the preceding paragraphs. Thus we have to take one more step and design the overall floor plan of the 12-bit A/D converter. An approximate view of the designed floor plan is given in Figure 8.6. As indicated in Figure 8.6 analog and digital pipeline stages are separated from each other in order to prevent analog signal processing from any noise caused by digital signal processing on substrate. That can degrade the overall efficiency of the analog block, hence, the resolution of the overall analog-to-digital converter. In between the analog and digital pipeline stages we placed the clock and
Figure 8.4 Assignment of clock signal/power distribution to different metal layers.

Figure 8.5 Lattice network consisting of clock and power distribution grids.
signal routing channels (Figure 8.6). We also separated the analog and digital signal pins as a result of the placement of the pipeline stage’s sub-blocks. Figure 8.6 also shows that both the analog and digital pipeline stage blocks are placed in a sequential manner from left to right in order to minimize the routing metal line lengths, thus the capacitive load due to the parasites on these tracks. Thus, we placed the flash A/D converter, the resistor and comparator chains, at the far left hand side of the sub-block in a vertical line-up. Note that the y-dimension of the flash A/D converter is determined by the y-dimension of the fifteen voltage comparators. Outputs of these comparators drive both the encoder and multiplying DAC inputs. But the output of the MDAC is
processed in the following analog pipeline stage, so that we placed the encoder sub-block next to right hand side of the A/D converter and then the multiplying D/A converter in a horizontal manner. We only repeat this block in order to construct the four pipeline stages. As in the same manner we placed the digital pipeline stages as the analog part. We constructed the digital pipeline stages in the same vertical axis with the related analog pipeline stage (Figure 8.6). Note that size of the digital pipeline stages decreases with the increasing stage number just because of the decreasing digital pipeline depth (four in the first stage and one in the last stage). We designed the digital pipeline stages by vertically repeating two horizontally designed “rows” that are formed by D-type flip-flops (DFFs) and full adder circuits (FAs) one after another (Figure 8.1). Consequently the analog signals flow from left to right, while the digital signals flow from top to bottom throughout the chip. Finally we used both the left and right side pins of the package for clock and power signals, which will work in a harmony with the lattice shaped distribution network we designed for these signals.

The overall silicon area that is occupied by these analog and digital pipeline stages is estimated to be about 0.25 mm$^2$, excluding the I/O pad-ring.
9. CONCLUSIONS

This thesis has presented the design, verification, system integration and the physical realization of a monolithic high-speed analog-digital converter (ADC) with 12-bit accuracy. The architecture of the ADC has been realized as a pipelined structure consisting of four pipeline stages, each of which is capable of processing the incoming analog signal with 4-bit accuracy. A bit-overlapping technique has been employed for digital error correction between the pipeline stages so that the influence of possible errors that occur during analog signal processing can be minimized. The entire circuit architecture is built with a modular approach, consisting of identical blocks organized into an easily expandable pipeline chain.

To realize the proposed circuit architecture, four basic building blocks were required: (i) high-speed voltage comparators, (ii) very high bandwidth op-amps with low offset, (iii) high-speed multiplying DAC (capacitive MDAC), and (iv) the digital correction circuitry including a 11-bit ripple carry adder. Initially, these key components were designed to meet the desired specifications, and then, the overall physical design of the ADC has been constructed by following a simple modular approach.

The voltage comparator is one of the main components that dictate the resolution of the overall A/D converter as well as the conversion speed of the converter. Several different topologies were studied; all of which were derived from the same basic structure. The full complementary circuit architecture was chosen as the final design, aided with a simple inverter based output stage to further improve the response times. The worst-case input voltage offset of the improved complementary comparator was
found to be less than 10 mV, allowing conversion with 7-bit accuracy at a dynamic input range of 1.6 V_pp. The worst-case INL and DNL errors remain within ±0.1 LSB for this 4-bit application due to the fact that the maximum input offset does not exceed 10 mV. Typical response times obtained for this voltage comparator are less than 450 ps, allowing operation speeds of up to 1 GHz. The circuit occupies a silicon area of about 320 μm² and consumes 800 μW at 200 MHz sampling frequency.

Using the designed voltage comparator as the main building block, a 4-bit flash A/D converter was built which is capable of operating at sampling clock frequencies up to 800 MHz with a signal-to-noise ratio of greater than 22.84 dB. It was verified that the designed 4-bit flash A/D converter is capable of processing input signal frequencies up to 80 MHz with 200 MHz sampling clock rate. Typical INL and DNL errors are less than 0.015 LSB and 0.025 LSB respectively.

Two possible implementations have been studied for the residue amplifier, which is one of the most important sub-blocks of a pipelined A/D converter. The single ended OTA-based circuit architecture was preferred in both of the designed versions, using a 1.8 V single power supply. The open-loop unity-gain frequency of the designed high gain op-amp is 2.16 GHz, while its open-loop gain is approximately 48.5 dB. Consequently its closed-loop 3dB frequency is 665 MHz, and input referred offset is 1.2 mV. The second implementation is a unity-gain stable (low gain) op-amp with an open-loop gain of 33.4 dB and 1.4 GHz unity gain frequency. Its closed-loop (unity gain configuration) 3dB frequency is 1.43 GHz. The input referred offset of the second op-amp implementation is less than 4 mV. With these operational characteristics, both of the designed op-amps are suitable for 12-bit data conversion at 200 MHz sampling clock frequency.

D/A converters play a very critical role in pipelined ADC architectures. Resolution and conversion speed mostly depend on how fast and accurate the DAC can generate its response. Based on the residue amplifier blocks described above, the typical response time of the monotonic MDAC (multiplying DAC) that was designed for this architecture is about 400 ps, allowing 200 MHz operation speed in the analog pipeline.

Finally, the performance of the digital pipeline depends critically on the response time of the error correction circuit that includes the 11-bit adder chain. Totally symmetric 1-bit full adder circuits were designed and used in a ripple-carry adder chain to facilitate the required 11-bit addition. Typical response time of the eleventh carry-out signal is about 1.8 ns, which is sufficient for operation at 200 MHz clock frequency.
All analog as well as digital sub-blocks of the ADC architecture presented in this work operate on a single clock signal (and its inverse), which significantly simplifies the design while ensuring a more robust performance. Other important features of this ADC include small area, single power supply, low power consumption, capability to operate at very high sampling clock rates, and the ability to handle a wide range of input signal amplitudes. The analog processing modules were designed using single-ended signals and the single-ended building blocks (as opposed to differential signals and building blocks) for simplicity. The ADC architecture was realized using a conventional 0.18 micron digital CMOS technology (Foundry: UMC), which ensures a lower overall cost and better portability for the design.

The ADC architecture presented in this work is capable of operating at sampling frequencies of up to 200 MHz, and still can achieve the nominal bit-resolution that was intended for 12-bit accuracy. The entire circuit is designed with single 1.8 V power supply. The maximum range of the input signal amplitude that the ADC can handle is 1.6 Vpp, with 1.8 V supply voltage. The input signal range as well as the operating points of critical components can be adjusted externally using dedicated control pins. The overall power consumption is estimated as 67.5 mW at 200 MHz sampling rate. Each 4-bit pipeline stage consists of a 4-bit flash A/D converter, a fully capacitive multiplying DAC (MDAC) and the corresponding digital encoding circuitry. The overall silicon area of the ADC is approximately 0.25 mm².

To summarize, the ADC architecture presented in this thesis is intended as a state-of-the-art data converter for very high-speed applications such as digital video transmission or high bandwidth wireless communication needs. It can be used either as a stand-alone single-chip unit, or as an embedded IP block that can be integrated with other modules in various SOI (system-on-chip) applications.
APPENDIX A

LITERATURE SURVEY ON ANALOG-TO-DIGITAL CONVERTERS
<table>
<thead>
<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>75</td>
<td>12</td>
<td>20kHz</td>
<td>-0.1</td>
<td>300mW</td>
<td>Pipeline</td>
<td>&quot;A High precision Component Tolerant ADC&quot;</td>
<td>90*125mil</td>
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<tr>
<td>75</td>
<td>16</td>
<td>200MHz</td>
<td>3%</td>
<td>0.9W</td>
<td>Gray code parallel</td>
<td>&quot;A Monolithic voltage comparator array for A/D Converters&quot;</td>
<td>98*104mil</td>
</tr>
<tr>
<td>76</td>
<td>11</td>
<td>20S/s</td>
<td>%0.0125</td>
<td>10V</td>
<td>Constant slope</td>
<td>&quot;An All MOS A/D Converter&quot;</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>77</td>
<td>50S/s</td>
<td>%0.01</td>
<td>30mW</td>
<td>Monolithic charge balancing</td>
<td>Analog meters to digital meters</td>
<td>131*133  mils</td>
</tr>
<tr>
<td>Dec</td>
<td>78</td>
<td>40kHz</td>
<td>no missing codes</td>
<td>18V</td>
<td>Monolithic I2L LWT Thin film resistor</td>
<td>&quot;A Charge-Balancing Monolithic A/D Converter&quot;</td>
<td>109*151 mils</td>
</tr>
<tr>
<td>Dec</td>
<td>78</td>
<td>20MHz</td>
<td>%0.1</td>
<td>6mW</td>
<td>C2MOS dual slope integrating</td>
<td>&quot;A Monolithic 10 Bit A/D Using I2L and LWT Thin Film Resistors&quot;</td>
<td>4.3*3.9 mils</td>
</tr>
<tr>
<td>Dec</td>
<td>78</td>
<td>1MHz</td>
<td>1 LSB</td>
<td>All MOS monolithic resistor string converter</td>
<td>&quot;A New Single Chip C2mos A/D converter for microprocessor Sys...&quot;</td>
<td>14000 mil2</td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td>79</td>
<td>1kHz</td>
<td>0.52 LSB</td>
<td>cascades of several folding amp, sigs</td>
<td>Video applications nonlinear version for PCM speech encoding</td>
<td>210*127 mils</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>79</td>
<td>640kHz</td>
<td>1/2 LSB</td>
<td>25mW</td>
<td>Monolithic charge balancing</td>
<td>&quot;A High speed 8 bit A/D converter based on a gray-code multiple...&quot;</td>
<td>2.4*3.2 mm2</td>
</tr>
<tr>
<td>Dec</td>
<td>79</td>
<td>20MHz</td>
<td>0.5 LSB</td>
<td>50mW</td>
<td>Flash 4um</td>
<td>Video bandwidth compression radar signature analysis, transient analy. Storage of osc. traces or relative data distortion analysis and high speed multiplexed data transition.</td>
<td>6.5*6.7 mm2</td>
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<tr>
<td>Dec</td>
<td>80</td>
<td>30MHz</td>
<td>full 8b linear</td>
<td>2.5mW</td>
<td>Monolithic fully parallel</td>
<td>High speed data communication, antialiasing filter</td>
<td>3mm2</td>
</tr>
<tr>
<td>Feb</td>
<td>80</td>
<td>200S/s</td>
<td>1%</td>
<td>400mW</td>
<td>Constant slope with external cap</td>
<td>&quot;An NMOS Microcomputer *Peripheral Interface Unit In ADC&quot;</td>
<td>2.5*3 mm2</td>
</tr>
<tr>
<td>June</td>
<td>80</td>
<td>100MHz</td>
<td>full 8-bit linearity</td>
<td>850mW</td>
<td>Monolithic comparator arrays in parallel</td>
<td>&quot;Monolithic Components for 100MHz Data Conversion&quot;</td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Bit</td>
<td>Sampling Rate</td>
<td>Linearity</td>
<td>Power</td>
<td>Architecture</td>
<td>Applications</td>
<td>Die Size</td>
</tr>
<tr>
<td>------</td>
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<td>--------------</td>
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<td>---------</td>
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<tr>
<td>June. Pg 295</td>
<td>8</td>
<td>13.2ns</td>
<td>pm1/2LSB</td>
<td>100mW</td>
<td>successive aprox.</td>
<td>&quot;A High Speed NMOS AID Converter with a Current Source Array&quot;</td>
<td>4mm2</td>
</tr>
<tr>
<td>Dec. pg 1040</td>
<td>12</td>
<td>25ns</td>
<td>0.2 LSB</td>
<td>40mW</td>
<td>Monolithic</td>
<td>&quot;Circuit Techniques for Achieving High-Speed - High Resolution AID Converters&quot;</td>
<td>39000 mil2</td>
</tr>
<tr>
<td>Dec. pg 949</td>
<td>12</td>
<td>50ns</td>
<td>0.1 LSB</td>
<td>100mW</td>
<td>Successive aprox. 3 IC</td>
<td>&quot;A Fast Latching Comparator for 12Bit AID Applications&quot;</td>
<td>23000 mil2</td>
</tr>
<tr>
<td>Dec. pg 938</td>
<td>7</td>
<td>50MHz</td>
<td>2 step parallel latching comp.</td>
<td>520mW</td>
<td></td>
<td>&quot;A High-Speed 7Bit AID Converter&quot;</td>
<td>2.4*2.5 mm2</td>
</tr>
<tr>
<td>Dec. pg 1088</td>
<td>12</td>
<td>2MHz</td>
<td>0.2 LSB</td>
<td>120mW</td>
<td>Successive aprox. sensing the polarity of input current</td>
<td>&quot;A Fast Latching Current Comparator for 12Bit AID Applications&quot;</td>
<td>63000 mil2</td>
</tr>
<tr>
<td>Dec. pg 1112</td>
<td>14</td>
<td>44.1kHz</td>
<td>pm1/4LSB</td>
<td>450mW</td>
<td>successive aprox. dynamic ele. match</td>
<td></td>
<td>3.5*4.4 mm2</td>
</tr>
<tr>
<td>Dec. pg 842</td>
<td>8</td>
<td>100MHz</td>
<td>pm1/3LSB</td>
<td>1.2W</td>
<td>Flash</td>
<td>hifi audio coding systems with high overall S/N ratio, low distortion, high temp stability of reference source</td>
<td>4.15*5.35 mm2</td>
</tr>
<tr>
<td>Dec. pg 965</td>
<td>13</td>
<td>12MHz</td>
<td>Interpolative pulse density modulator</td>
<td>20mW</td>
<td></td>
<td>allows applications of this comp.to industrial &amp; other professional systems.</td>
<td>2.0*1.45 mm2</td>
</tr>
<tr>
<td>Dec. pg 723</td>
<td>10</td>
<td>20MHz</td>
<td>pm1/2LSB</td>
<td>2W</td>
<td>Fully parallel</td>
<td>Video speed TV systems.</td>
<td>9.2*9.8 mm2</td>
</tr>
<tr>
<td>June. pg 374</td>
<td>14</td>
<td>50kHz</td>
<td>0.2LSB</td>
<td>450mW</td>
<td>Monolithic dual channel, coarse-fine integration</td>
<td>&quot;A Fully Parallel 10Bit AD Converter...&quot;</td>
<td>3.35*3.35 mm2</td>
</tr>
<tr>
<td>Dec. pg 337</td>
<td>8</td>
<td>120MHz</td>
<td>1/4LSB</td>
<td>2W</td>
<td>Flash</td>
<td>PCM audio systems.</td>
<td></td>
</tr>
<tr>
<td>June. pg 374</td>
<td>8</td>
<td>520mW</td>
<td>2 step parallel Flash</td>
<td>Video</td>
<td>&quot;A Monolithic 8 Bit Video AD Converter&quot;</td>
<td>3*4.2 mm2</td>
<td></td>
</tr>
</tbody>
</table>

Table A.2
<table>
<thead>
<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>8</td>
<td>20MHz</td>
<td>pm1/2LSB</td>
<td>350mW</td>
<td>Fully parallel</td>
<td>Video: A CMOS HIGH Speed A/D Converter IC</td>
<td>4.8*6.3 mm2</td>
</tr>
<tr>
<td>June. Pg 775</td>
<td>8</td>
<td>200MHz</td>
<td>pm0.1LSB</td>
<td>1.1W</td>
<td>Full Flash</td>
<td>&quot;A 6bit 200MHz Fully Nyquist A/D Converter&quot;</td>
<td>4*2.2 mm2</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8MHz</td>
<td>0.3LSB</td>
<td>20mW</td>
<td>Subranging</td>
<td>Video, digital signal processing. &quot;An 8 bit CMOS Subranging ADC&quot;</td>
<td>3.2*2.2 mm2</td>
</tr>
<tr>
<td>Dec. pg 1138</td>
<td>8</td>
<td>20MHz</td>
<td>&lt;pm0.5LSB</td>
<td>150mW</td>
<td>1st order self calibrat.</td>
<td>&quot;Process control, medical, scientific instruments digital audio etc.&quot;</td>
<td>3*1.1 mm2</td>
</tr>
<tr>
<td>April. pg 318</td>
<td>8</td>
<td>20MHz</td>
<td>approx.14b</td>
<td>60mW</td>
<td>Flash</td>
<td>Video systems, TV's VCR's</td>
<td>3.08*2.56 mm2</td>
</tr>
<tr>
<td></td>
<td>14</td>
<td>12MHz</td>
<td></td>
<td></td>
<td></td>
<td>&quot;A Compatible CMOS-JFET Pulse Density Modulator for ...&quot;</td>
<td>1800 mil2</td>
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<tr>
<td>June. Pg 446</td>
<td>12</td>
<td>2.5MHz</td>
<td>pm1/2LSB</td>
<td></td>
<td></td>
<td>&quot;A 12 bit Successive Approximation Type ADC with Digital Error Correction&quot;</td>
<td>2.7 mm2</td>
</tr>
<tr>
<td>Dec. pg 1016</td>
<td>10</td>
<td>&lt;pm0.6LSB</td>
<td>Switched capacitor 4u</td>
<td>150uW</td>
<td></td>
<td>telemetry, instrumentation measurements require high accuracy, excellent linearity, negligible dc offset, speech audio, video.</td>
<td></td>
</tr>
<tr>
<td>April. pg 157</td>
<td>6</td>
<td>&lt;1/6LSB</td>
<td>2 stage Flash</td>
<td></td>
<td></td>
<td>&quot;Monotonic Dual-Ladder AD Conversion&quot;</td>
<td></td>
</tr>
<tr>
<td>April. pg 295</td>
<td>16</td>
<td>&lt;3MHz</td>
<td>110mW</td>
<td></td>
<td></td>
<td>High quality audio &amp; high accuracy measurement systems.</td>
<td>2.7*2.7 mm2</td>
</tr>
<tr>
<td>Dec. pg 921</td>
<td>6</td>
<td>30MHz</td>
<td>&lt;pm1/2LSB</td>
<td>12mW</td>
<td>Flash</td>
<td>Video freq. video &amp; measuring equip., liquid crystal TVs portable measuring equip. Such as digital osc. and professional systems.</td>
<td>1.5 mm2</td>
</tr>
<tr>
<td>Dec. pg 939</td>
<td>8</td>
<td>55MHz</td>
<td>300mW</td>
<td></td>
<td></td>
<td>&quot;A 12mV6 bit Video Frequency A/D Converter&quot;</td>
<td>6 mm2</td>
</tr>
<tr>
<td>Dec. pg 944</td>
<td>9</td>
<td>5MS/s</td>
<td>&lt;0.6LSB</td>
<td>180mW</td>
<td>Pipelined</td>
<td>Complex high-speed image processing. &quot;An 8 bit Video ADC Incorporating Folding and Interpolating ...&quot;</td>
<td>8500 mil2</td>
</tr>
<tr>
<td>Dec. pg 962</td>
<td>0</td>
<td>1GHz</td>
<td>pm0.3LSB</td>
<td>16W</td>
<td>Interleaved</td>
<td>Digitizing oscilloscopes. &quot;A 1 GHz 6 bit ADC System&quot;</td>
<td>2.2*3.5 mm2</td>
</tr>
<tr>
<td>June. pg 436</td>
<td>7</td>
<td>30MS/s</td>
<td>pm0.5LSB</td>
<td>350mW</td>
<td>Flash</td>
<td>Digital video signal processing, high speed data conversion</td>
<td>3.5*3.6 mm2</td>
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Table A.3
<table>
<thead>
<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>12</td>
<td>1MS/s</td>
<td>12bit</td>
<td>400mW</td>
<td>Pipelined</td>
<td>High performance medical, industrial and military applications.</td>
<td>14 mm²</td>
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<tr>
<td>Dec. pg 1324</td>
<td></td>
<td></td>
<td>linearity</td>
<td></td>
<td>cap-array averaging</td>
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<tr>
<td>88</td>
<td>14</td>
<td>100kHz</td>
<td>0.5LSB</td>
<td>480mW</td>
<td>Subranging</td>
<td>&quot;A 14bit 10us Subranging A/D Converter with S/H&quot;</td>
<td>2600*290 mil</td>
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<tr>
<td>Dec. pg 1309</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Flash</td>
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<tr>
<td>88</td>
<td>8</td>
<td>8kHz</td>
<td>0.5LSB</td>
<td>5V</td>
<td>Cyclic 2um</td>
<td>&quot;A Cyclic A/D Converter that Does Not Require Ratio-Matched Components&quot;</td>
<td>0.79 mm²</td>
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<tr>
<td>Feb. pg 152</td>
<td></td>
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<tr>
<td>88</td>
<td>15</td>
<td>&lt;0.3LSB</td>
<td>325uW</td>
<td></td>
<td>2nd order offset &amp; charge injection comp. ΣΔ</td>
<td>Telecommunication, dedicated to applications which can tolerate offset &amp; gain errors.</td>
<td>4.6 mm²</td>
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<tr>
<td>June. Pg 738</td>
<td></td>
<td></td>
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<tr>
<td>88</td>
<td>13</td>
<td>250kS/s</td>
<td>0.5LSB</td>
<td>15mW</td>
<td>Pipelined</td>
<td>high speed telecommunication sys./ISDN, applications that require complex signal processing.</td>
<td>3400 mm²</td>
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<tr>
<td>Dec. pg 1318</td>
<td></td>
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<tr>
<td>88</td>
<td>4</td>
<td>1G/s</td>
<td>1LSB</td>
<td>2.4mW</td>
<td>Flash</td>
<td>Video.</td>
<td>1.5*2.9</td>
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<tr>
<td>June pg 742</td>
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<td></td>
<td></td>
<td></td>
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<td>mm²</td>
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<tr>
<td>88</td>
<td>4</td>
<td>&gt;20GHz</td>
<td>periodic-threshold</td>
<td></td>
<td>Josephson</td>
<td>&quot;A New High Speed Periodic Threshold Comparator for ...&quot;</td>
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<tr>
<td>Aug. pg 1017</td>
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<tr>
<td>88</td>
<td>8</td>
<td>100MHz</td>
<td>0.5LSB</td>
<td>800mW</td>
<td>Folding &amp; interpolating</td>
<td>is used to optimize the speed of converter with respect to technology used.</td>
<td>3.2*3.8</td>
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<td>Dec. pg 1334</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td>mm²</td>
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<tr>
<td>88</td>
<td>4</td>
<td>1MS/s</td>
<td>&lt;pm0.4LSB</td>
<td>18mW</td>
<td>Flash (SOI)</td>
<td>&quot;A SOI Structure for Flash A/D Converter&quot;</td>
<td>1.25*3.00 mm²</td>
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<tr>
<td>Feb. pg 198</td>
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<tr>
<td>00</td>
<td>10</td>
<td>15MHz</td>
<td>1.1/0.8LSB</td>
<td>250mW</td>
<td>2 step recycling</td>
<td>video signal processing, high quality video reproduction, image recognition X-ray, ultrasonic imaging, digital instrumentation, radar, digital radio tape, HDTV.</td>
<td>1.75 mm²</td>
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<td></td>
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<tr>
<td>90</td>
<td>10</td>
<td>75MS/s</td>
<td>pm1LSB</td>
<td>2W</td>
<td>2 step fully diff. subranging</td>
<td>consumer oriented TV-digital video signal processing in professional imaging sys., HDTV</td>
<td>4.8*4.2</td>
</tr>
<tr>
<td>Dec. pg 1339</td>
<td></td>
<td></td>
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<td></td>
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<td>mm²</td>
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<tr>
<td>89</td>
<td>10</td>
<td>20MHz</td>
<td>pm0.5LSB</td>
<td>900mW</td>
<td>2 step parallel</td>
<td>high quality video sys., high definition video sys., video tape recorder for business, digital video cameras.</td>
<td>25 mm²</td>
</tr>
<tr>
<td>Feb. pg 13</td>
<td></td>
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<tr>
<td>89</td>
<td>10</td>
<td>5MS/s</td>
<td>0.5LSB</td>
<td>350mW</td>
<td>2 step fully diff. Flash</td>
<td>&quot;A 10b 5MS/s CMOS Two Step Flash ADC&quot;</td>
<td>54000 mm²</td>
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<tr>
<td>April pg 241</td>
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Table A.4
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<th>Year</th>
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<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Applications</th>
<th>Die Size</th>
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<tr>
<td>Dec 89</td>
<td>12</td>
<td>500ns/4b</td>
<td>0.02%</td>
<td>650mW</td>
<td>Subranging</td>
<td>Digital signal processing</td>
<td>&quot;A 12bit 1 MHz Two-Step ADC&quot;</td>
<td>25mm²</td>
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<tr>
<td>April pg 250</td>
<td>12</td>
<td>1MHz</td>
<td>0.5LSB</td>
<td>750mW</td>
<td>2 step Flash</td>
<td>ISDN, interface transceivers, modems, digital audio, tape (DAT), compact disc (CD) players, sonar signal processing.</td>
<td></td>
<td>9.5*8.4mm²</td>
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<tr>
<td>April pg 256</td>
<td>14</td>
<td>80kHz</td>
<td></td>
<td>76mW</td>
<td>ΣΔ</td>
<td>ISDN, digital audio.</td>
<td>&quot;A 16bit 160kHz CMOS A/D Converter Using Sigma-Delta...&quot;</td>
<td>2mm²</td>
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<tr>
<td>April pg 431</td>
<td>16</td>
<td>1.6MHz</td>
<td></td>
<td>76mW</td>
<td>1st order 1.5um ΣΔ</td>
<td>Experimental for FIB.</td>
<td>&quot;A Monolithic 20Bit Delta-Sigma A/D Converter&quot;</td>
<td>3mm²</td>
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<tr>
<td>April pg 562</td>
<td>4</td>
<td>&gt;1GHz</td>
<td>pm0.5LSB</td>
<td>&lt;100mW</td>
<td>Flash</td>
<td>&quot;A Deep-Submicrometer Analog to Digital Converter Using...&quot;</td>
<td></td>
<td>0.91mm²</td>
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<tr>
<td>June pg 617</td>
<td>8</td>
<td>7.5 to 15/s</td>
<td>2 counts</td>
<td>50mW</td>
<td>Monolithic 3 step conversion</td>
<td>digital voltmeter, precision measurements recording DC or low freq. quantities (up to 22 bits)</td>
<td></td>
<td>5.6*3.8mm²</td>
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<tr>
<td>Dec pg 1311</td>
<td>20</td>
<td>250kHz</td>
<td></td>
<td>125mW</td>
<td>4th order monolithic ΣΔ</td>
<td>&quot;A Monolithic 20bit Delta-Sigma A/D Converter&quot;</td>
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<td>29.25mm²</td>
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<tr>
<td>June pg 880</td>
<td>8</td>
<td>1.3MHz</td>
<td>&lt;1LSB</td>
<td>70mW</td>
<td>Pipelined successive app.</td>
<td>&quot;An 8bit 1.3MHz Successive-Approximation A/D Converter&quot;</td>
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<td>3750mm²</td>
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<tr>
<td>Feb pg 167</td>
<td>8</td>
<td>20MS/s</td>
<td>pm0.5LSB</td>
<td>60mW</td>
<td>2 stage pipelined subranging</td>
<td>Video systems</td>
<td>&quot;An 8bit20MS/s CMOS A/D Converter with 50mW Power Consup.&quot;</td>
<td></td>
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<tr>
<td>Dec pg 1485</td>
<td>8</td>
<td>50MHz</td>
<td></td>
<td>600mV</td>
<td>Pipelined subranging with S/H</td>
<td>Video signal processing</td>
<td>&quot;An 8bit 50MHz CMOS Subranging A/D Converter with ...&quot;</td>
<td></td>
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<tr>
<td>Mar pg 351</td>
<td>10</td>
<td>20MS/s</td>
<td>0.2LSB</td>
<td>240mV</td>
<td>9 stage pipelined fully diff.</td>
<td>&quot;A 10b 20MS/s Analog to Digital Converter&quot;</td>
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<td>8.7mm²</td>
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<tr>
<td>Dec pg 1687</td>
<td>12</td>
<td>5MS/s</td>
<td>0.7LSB</td>
<td>200mV</td>
<td>2 stage flash fully diff. 1um</td>
<td>&quot;A 12b 750ns Subranging A/D Converter with Self Correcting...&quot;</td>
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<td>2.5*3.7mm²</td>
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<tr>
<td>Dec pg 1790</td>
<td>12</td>
<td>1.6MHz</td>
<td>pm0.5LSB</td>
<td>600mV</td>
<td>Multiple flash subranging</td>
<td>wide dynamic range imaging, high resolution video.</td>
<td>&quot;A 13b 2.5MHz Self-Calibrated Pipelined A/D converter ...&quot;</td>
<td></td>
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<tr>
<td>April pg 628</td>
<td>13</td>
<td>2.5MHz</td>
<td>0.4/-0.6LSB</td>
<td>100mW</td>
<td>Pipelined self-calibrated 3um</td>
<td>&quot;A 13b 2.5MHz Self-Calibrated Pipelined A/D converter ...&quot;</td>
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<td>26mm²</td>
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Table A.5
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<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
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<tbody>
<tr>
<td>Dec. pg 1781</td>
<td>8</td>
<td>4GHz</td>
<td>pm1/4LSB</td>
<td></td>
<td>sample &amp; filter</td>
<td>high sampling devices, digitizing oscilloscopes</td>
<td>0.65</td>
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<tr>
<td>Dec. pg 1746</td>
<td>12</td>
<td>2MHz</td>
<td></td>
<td>41mW</td>
<td>cascaded multibit</td>
<td>&quot;A 50MHz Multibit Sigma-Delta Modulator for 12b 2MHz A/D Conv.&quot;</td>
<td>2.9</td>
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<tr>
<td>July. pg 957</td>
<td>13</td>
<td>25k/s/s</td>
<td>1.2LSB</td>
<td>45mW</td>
<td>cyclic redundant</td>
<td>&quot;A CMOS 13b Cyclic RSD A/D Converter&quot;</td>
<td>3</td>
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<tr>
<td>Oct. pg 1313</td>
<td>5</td>
<td>1GS/s</td>
<td>pm0.4LSB</td>
<td>3400mW</td>
<td>signed digit</td>
<td>measurement technology, HDTV, digital broadcasting, radar technology</td>
<td>3*3</td>
</tr>
<tr>
<td>July. pg 910</td>
<td>20</td>
<td>0.25LSB</td>
<td></td>
<td>6.7mW</td>
<td>Flash</td>
<td>&quot;A Monoithic CMOS 20b Analog to Digital Converter&quot;</td>
<td>1.4</td>
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<tr>
<td>Aug. pg 1103</td>
<td>10</td>
<td>20MS/s</td>
<td>1LSB</td>
<td>1W</td>
<td>Pipelined 2um</td>
<td>ultrasound &amp; infrared imagers</td>
<td>0.35*7.61</td>
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<tr>
<td>Dec. pg 10662</td>
<td>8</td>
<td>650MHz</td>
<td>&lt;0.5LSB</td>
<td>850mW</td>
<td>Folding</td>
<td>&quot;An 8b 650MHz Folding A/D&quot;</td>
<td>4.2</td>
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<tr>
<td>Mar. pg 292</td>
<td>10</td>
<td>50MHz</td>
<td>pm0.5LSB</td>
<td>900mW</td>
<td>3 stage pipelined</td>
<td>HDTV, video signal processing, VCRs &amp; encoders</td>
<td>6*3</td>
</tr>
<tr>
<td>Dec. pg 1531</td>
<td>10</td>
<td>20MS/s</td>
<td>pm0.5LSB</td>
<td>135mW</td>
<td>Pipelined multistage</td>
<td>&quot;A 10b 50MHz Pipelined CMOS A/D Converter With S/H&quot;</td>
<td>3.5*2.0</td>
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<tr>
<td>Dec. pg 1180</td>
<td>10</td>
<td>100MS/s</td>
<td>pm0.5LSB</td>
<td>950mW</td>
<td>subranging 0.8um</td>
<td>HDTV video systems processing</td>
<td>3.4*5.6</td>
</tr>
<tr>
<td>Dec. pg 1200</td>
<td>10</td>
<td>20MHz</td>
<td>pm0.5LSB</td>
<td>30mW</td>
<td>pipelined interpolating</td>
<td>&quot;A 10b 20MS/s 30mW Pipelined Interpolating CMOS A/D&quot;</td>
<td>2.6*2.6</td>
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<tr>
<td>Apr. pg 515</td>
<td>10</td>
<td>300MHz</td>
<td>pm0.4LSB</td>
<td>4W</td>
<td>interpolating parallel &amp; folding 1um</td>
<td>high speed measurements, medical engineering systems &amp; HDTV systems</td>
<td>9.0*4.2</td>
</tr>
<tr>
<td>Dec. pg 1187</td>
<td>10</td>
<td>75MHz</td>
<td>pm0.5LSB</td>
<td>800mW</td>
<td>2 stage pipelined</td>
<td>&quot;A 10b 75MHz Two Stage Pipelined Bipolar A/D&quot;</td>
<td>4.4</td>
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<tr>
<td>Aug. pg 666</td>
<td>10</td>
<td>5MS/s</td>
<td>pm0.5LSB</td>
<td>18mW</td>
<td>successive approach</td>
<td>video signal processing, HDTVs</td>
<td>0.6</td>
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<tr>
<td>Aug. pg 987</td>
<td>10</td>
<td>650kHz</td>
<td>0.3LSB</td>
<td>20mW</td>
<td>pipelined switched current</td>
<td>&quot;A 10b Pipelined Switched-Current A/D Converter&quot;</td>
<td>2.5</td>
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Table A.6
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<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>93</td>
<td>Dec. pg 1606</td>
<td>0</td>
<td>100MHz</td>
<td>pm0.6LSB</td>
<td>25mW</td>
<td>Fully parallel</td>
<td>PRML magnetic disk read channel interface</td>
</tr>
<tr>
<td>94</td>
<td>Apr. pg 5059</td>
<td>12</td>
<td>600kS/s</td>
<td>pm0.6LSB pm1LSB</td>
<td>45mW</td>
<td>2 stage pipelined digital self calib. 1.6um</td>
<td>&quot;A 12b 600kS/s Digitally Self-Calibrated Pipelined Algorithmic ADC&quot;</td>
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<tr>
<td>93</td>
<td>Dec. pg 1207</td>
<td>15</td>
<td>1MS/s</td>
<td>pm0.25LSB pm1.25LSB</td>
<td>1.8W</td>
<td>Pipelined digitally self calib. 2.4um</td>
<td>&quot;A 15b 1MSample/s Digitally Self-Calibrated Pipelined ADC&quot;</td>
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<tr>
<td>93</td>
<td>June pg 640</td>
<td>16</td>
<td>320kHz</td>
<td></td>
<td>65mW</td>
<td>3rd order 2 stage</td>
<td>audio applications</td>
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<tr>
<td>94</td>
<td>Aug. pg 879</td>
<td>8</td>
<td>25MS/s</td>
<td>0.5LSB DNL 0.5LSB INL</td>
<td>540mW</td>
<td>Full flash 1um</td>
<td>&quot;A 12b 320kHz CMOS AD Converter Using Two Stage...&quot;</td>
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<tr>
<td>94</td>
<td>Aug. pg 873</td>
<td>6</td>
<td>80MS/s</td>
<td>0.5LSB DNL 0.5LSB INL</td>
<td>400mW</td>
<td>Flash 1um</td>
<td>Sensors, tuners, display electronics, power amplifiers, display drivers</td>
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<tr>
<td>94</td>
<td>Aug. pg 857</td>
<td>16</td>
<td>48MHz</td>
<td></td>
<td>180mW</td>
<td>4th order 3 stage</td>
<td>&quot;A High Frequency and High Resolution Fourth Order Sigma-Delta AD Converter in BICMOS Technology&quot;</td>
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<tr>
<td>93</td>
<td>July. pg 725</td>
<td>8</td>
<td>13.5MHz</td>
<td>pm1LSB</td>
<td>150mW</td>
<td>Half flash subranging 1um</td>
<td>&quot;A Low Power 8b 13.5MHz Video CMOS ADC for Visiophony...&quot;</td>
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<td>91</td>
<td>Apr. pg 455</td>
<td>12</td>
<td>200kHz</td>
<td>pm1.2LSB</td>
<td>10mW</td>
<td>Fully differential 1um</td>
<td>&quot;A Low Power 12b Analog to Digital Converter with On Chip...&quot;</td>
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<td>94</td>
<td>Dec. pg 1514</td>
<td>5</td>
<td>500kHz</td>
<td></td>
<td>180mW</td>
<td>4th order 3 stage</td>
<td>&quot;A Stereo Audio Sigma-Delta Converter&quot;</td>
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<td>96</td>
<td>Sep. pg 1336</td>
<td>8</td>
<td>1.2GS/s</td>
<td></td>
<td>460mW</td>
<td>monolithic</td>
<td>digitizing oscilloscopes</td>
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<tr>
<td>95</td>
<td>Oct. pg 1507</td>
<td>10</td>
<td>20MS/s</td>
<td>0.6LSB</td>
<td>35mW</td>
<td>pipelined 1.2um</td>
<td>&quot;A 12b 20MS/s Silicon Bipolar Track &amp; Hold IC&quot;</td>
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<tr>
<td>95</td>
<td>May pg 514</td>
<td>10</td>
<td>20MS/s</td>
<td>pm0.6LSB</td>
<td>50mW</td>
<td>8 identical unscaled pipelined 1.2um</td>
<td>Portable video devices camcorders, personal computers, wireless LAN transceivers, read channels of magnetic storage devices.</td>
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<tr>
<td>96</td>
<td>Oct. pg 1507</td>
<td>10</td>
<td>40MS/s</td>
<td>0.3/-0.6LSB 0.6/-0.9LSB</td>
<td>&lt;400mW</td>
<td>Pipelined</td>
<td>High definition video reproduction computer graphics X-ray, medical imaging</td>
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<tr>
<td>Year</td>
<td>Bit</td>
<td>Sampling Rate</td>
<td>Linearity</td>
<td>Power</td>
<td>Architecture</td>
<td>Applications</td>
<td>Die Size</td>
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<tr>
<td>Jan. pg 70</td>
<td>14</td>
<td>25MS/s</td>
<td>pm0.5LSB</td>
<td>500mW</td>
<td>Pipelined</td>
<td>applications such as high&amp;still imaging CCD,PMT,high data rate digital communication over twisted pair ADSL</td>
<td>5.4*4.4 mm²</td>
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<tr>
<td>July. pg 933</td>
<td>8</td>
<td>175MS/s</td>
<td>1/0.8LSB</td>
<td>160mW</td>
<td>Full flash 0.7um continuous time analog</td>
<td>mixed signal processing systems with feedback</td>
<td>12 mm²</td>
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<td>10</td>
<td>20MS/s</td>
<td>pm0.5LSB</td>
<td>20mW</td>
<td>Subranging mixed mode</td>
<td>&quot;A 175MS/s 6b 150mW 3.3V CMOS ADC&quot;</td>
<td>3.2*3.8 mm²</td>
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<tr>
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<td>10</td>
<td>200MHz</td>
<td>pm0.5LSB</td>
<td>15mW</td>
<td>SHA</td>
<td>video recorders,battery operated portable video systems</td>
<td>220*150 um²</td>
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<tr>
<td>Oct. pg</td>
<td>8</td>
<td>5GHz</td>
<td>pm0.5LSB</td>
<td>85mW</td>
<td>Bandpass</td>
<td>&quot;A 200MHz 15mW BICMOS S&amp;H Amplifier Unit 3V Supply&quot;</td>
<td>407*143 um²</td>
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<tr>
<td>Oct. pg 1109</td>
<td>8</td>
<td>4HS/s</td>
<td>pm0.5LSB</td>
<td>85mW</td>
<td>Folding</td>
<td>digitizing IF signals in wireless radio receiver</td>
<td>407*143 um²</td>
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<tr>
<td>Dec. pg 1302</td>
<td>8</td>
<td>70MS/s</td>
<td>pm0.2LSB</td>
<td>110mW</td>
<td>Folding&amp;interpolating 0.8um</td>
<td>&quot;A 70 MS/s 110mW 6b CMOS Folding and Interpolating...&quot;</td>
<td>0.7 mm²</td>
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<tr>
<td>Nov. pg 1834</td>
<td>8</td>
<td>200MS/s</td>
<td>pm0.3LSB</td>
<td>110mW</td>
<td>Flash 0.5um</td>
<td>PRML read channel LSI,partial response max. likelihood</td>
<td>0.8*2 mm²</td>
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<tr>
<td>Aug. pg 1201</td>
<td>14</td>
<td>10kHz</td>
<td>pm0.5LSB</td>
<td>50mW</td>
<td>Switched cap. algorithmic 0.6um</td>
<td>&quot;A CMOS 8b 200MS/s 3V Supply AD Converter for PRML ...&quot;</td>
<td>2.1*0.8 mm²</td>
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<td>May. pg 522</td>
<td>8</td>
<td>4.5MS/s</td>
<td>pm0.6LSB</td>
<td>18mW</td>
<td>Pipelined current mode</td>
<td>&quot;A CMOS Ratio Independent and Gain Inensitive Algorithmic ...&quot;</td>
<td>0.73 mm²</td>
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<td>July. pg 945</td>
<td>8</td>
<td>15MS/s</td>
<td>pm0.6LSB</td>
<td>350mW</td>
<td>Pipelined</td>
<td>&quot;A Fully Nyquist 15MS/s 6b Differential Switched Current A/D ...&quot;</td>
<td>2.4 mm²</td>
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<td>12</td>
<td>1MHz</td>
<td>pm0.6LSB</td>
<td>25mW</td>
<td>time interleaved multistage 0.3um</td>
<td>&quot;A Low Power 1MHz 12b Time Interleaved ADC&quot;</td>
<td>130*176 mil²</td>
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<td>Feb. pg 1201</td>
<td>14</td>
<td>30MHz</td>
<td>pm0.6LSB</td>
<td>270mW</td>
<td>multiple sampling</td>
<td>radio receivers,mixers,filters</td>
<td>6.4 mm²</td>
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<tr>
<td>Mar. pg 294</td>
<td>13</td>
<td>5MS/s</td>
<td>pm1LSB</td>
<td>166mW</td>
<td>Pipelined</td>
<td>medical imaging,high-speed data transmission sys.</td>
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<tr>
<td>Mar. pg 153</td>
<td>10</td>
<td>40MS/s</td>
<td>pm1LSB</td>
<td>85mW</td>
<td>Pipelined 0.8um</td>
<td>radio receivers,mixers,filters</td>
<td>1.9*2.1 mm²</td>
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Table A.8
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<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
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<tr>
<td>Sep pg 1248</td>
<td>8</td>
<td>125MS/s</td>
<td>0.6LSB</td>
<td>225mW</td>
<td>Folding current mode</td>
<td>HDTV, magnetic recording sampling detectors, medical imager, digital trans., links for telephone, cable &amp; terrestrial networks</td>
<td>4</td>
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<tr>
<td>95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&quot;CMOS Folding AID Converter with Current Mode Interpolation&quot;</td>
<td></td>
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<tr>
<td>Aug pg 1132</td>
<td>7</td>
<td>30M/Hz</td>
<td>&lt;1LSB</td>
<td>307.2mW</td>
<td>Flash</td>
<td>telecommunication &amp; instrumentation for time-domain analysis</td>
<td>1585*3037</td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&quot;Power Efficient Metastability Error Reduction in CMOS Flash...&quot;</td>
<td></td>
</tr>
<tr>
<td>Mar pg 3C2</td>
<td>10</td>
<td>100MS/s</td>
<td>0.7/-0.3LSB</td>
<td>1.1W</td>
<td>Parallel pipelined</td>
<td>&quot;A 10b 100MS/s CMOS AD Converter&quot;</td>
<td>50</td>
</tr>
<tr>
<td>Dec pg 1876</td>
<td>12</td>
<td>60MS/s</td>
<td>&lt;0.6LSB</td>
<td>300mW</td>
<td>cascaded folding &amp; interpolating</td>
<td>commercial &amp; industrial weigh scales</td>
<td>mm2</td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td>&lt;1.5LSB</td>
<td></td>
<td></td>
<td>&quot;A 12b 60MS/s Cascaded Folding and Interpolating ADC&quot;</td>
<td>7</td>
</tr>
<tr>
<td>July pg 989</td>
<td>3000count</td>
<td></td>
<td>0.0015/100</td>
<td>90mW</td>
<td>Transducer</td>
<td>&quot;A CMOS Soft-Switched Transconductor and its App...&quot;</td>
<td>2.73*4.68</td>
</tr>
<tr>
<td>98</td>
<td>14</td>
<td>5MHz</td>
<td></td>
<td>9.6mW</td>
<td>3rd order 0.6um,</td>
<td>audio</td>
<td>1.08</td>
</tr>
<tr>
<td>98</td>
<td>10</td>
<td>200kS/s</td>
<td>&lt;pm0.5LSB</td>
<td>12mW</td>
<td>Pipelined successive approx.</td>
<td></td>
<td>5.12</td>
</tr>
<tr>
<td>97</td>
<td>6</td>
<td>168MS/s</td>
<td>pm0.5LSB</td>
<td>505mW</td>
<td>Flash folded cascade FCDL</td>
<td>PRML</td>
<td>2.5*2.4</td>
</tr>
<tr>
<td>97</td>
<td>12</td>
<td>125kS/s</td>
<td>pm0.21LSB</td>
<td>10mW</td>
<td>digital back ground calibrated algorithm</td>
<td>&quot;A 12b Digital Background Calibrated Algorithmic ADC with ...&quot;</td>
<td>5.9</td>
</tr>
<tr>
<td>Dec pg 1812</td>
<td>8</td>
<td>100MS/s</td>
<td>0.7/-0.3LSB</td>
<td>1.1W</td>
<td>Parallel Pipelined</td>
<td>high end video signal, high performance digital communication, medical imaging</td>
<td>50</td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>data communication, storage QAM pR detection</td>
<td></td>
</tr>
<tr>
<td>March</td>
<td>6</td>
<td>52MS/s</td>
<td>1LSB</td>
<td>260mW</td>
<td>Parallel Pipelined</td>
<td>audio</td>
<td>25.8</td>
</tr>
<tr>
<td>97</td>
<td>24</td>
<td>48kHz</td>
<td>pm10LSB</td>
<td>500mW</td>
<td>ΣΔ 0.7um</td>
<td>Instrumentation and geoseismic survey applications</td>
<td>19</td>
</tr>
<tr>
<td>97</td>
<td>19</td>
<td>600Hz</td>
<td>10LSB</td>
<td>2.7mW</td>
<td>ΣΔ data weighted averag.</td>
<td>Industrial weigh scales</td>
<td>2.73*4.68</td>
</tr>
<tr>
<td>July pg 933</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&quot;A Low Noise Low Drift Transducer ADC&quot;</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Year</td>
<td>Bit</td>
<td>Sampling Rate</td>
<td>Linearity</td>
<td>Power</td>
<td>Architecture</td>
<td>Applications</td>
<td>Die Size</td>
</tr>
<tr>
<td>------</td>
<td>-----</td>
<td>---------------</td>
<td>-----------</td>
<td>-------</td>
<td>--------------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>Jul 97</td>
<td>4</td>
<td>4kHz</td>
<td></td>
<td>100mW</td>
<td>0.5um</td>
<td>teleconference systems, hands free telephone</td>
<td>50 mm²</td>
</tr>
<tr>
<td>Sep 97</td>
<td>6</td>
<td>160MS/s</td>
<td>&lt;pm0.5LSB</td>
<td>505mW</td>
<td>Flash</td>
<td>PRML read channels</td>
<td>2.5 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>15</td>
<td>5MS/s</td>
<td>0.75/-0.6LSB/1.77/-1.58</td>
<td>60mW</td>
<td>Pipelined</td>
<td>&quot;Error Suppression Encode Logic of FCDL in a 6b Flash ADC&quot;</td>
<td>27 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>12</td>
<td>60MS/s</td>
<td>0.25LSB</td>
<td>300mW</td>
<td>cascaded folding interpolating</td>
<td>&quot;A 12b 60MS/s Cascaded Folding and Interpolating ADC&quot;</td>
<td>7 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>10</td>
<td>50MS/s</td>
<td>0.5LSB</td>
<td>240mW</td>
<td>Flash</td>
<td>RF, IF radio filters</td>
<td>1.4 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>10</td>
<td>1.25MHz</td>
<td></td>
<td>550mW</td>
<td>∑Δ</td>
<td>&quot;An Embedded 240mW 10b 50MS/s CMOS ADC in 1mm²&quot;</td>
<td>5.7 mm²</td>
</tr>
<tr>
<td>Dec 98</td>
<td>8</td>
<td>200kS/s</td>
<td>pm4LSB</td>
<td>4.3uW</td>
<td>Pipelined</td>
<td>visual dat processing, hard disk controllers, handy dat terminals</td>
<td>0.52 mm²</td>
</tr>
<tr>
<td>Aug 98</td>
<td>10</td>
<td>200kS/s</td>
<td>1LSB</td>
<td>12mW</td>
<td>successive approximation</td>
<td>&quot;Design &amp; Implementation of a Untimed MOSIet only 10b ADC ...&quot;</td>
<td>5.12 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>16</td>
<td>255MHz</td>
<td>pm0.4LSB</td>
<td>200mW</td>
<td>subranging pipelined</td>
<td>PRML read channels</td>
<td>2.1 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>12</td>
<td>20MS/s</td>
<td>0.36LSB</td>
<td>250mW</td>
<td>self calibrating pipelined, 0.7um</td>
<td>&quot;A 900mW Low Power Delta-Sigma Converter with ...&quot;</td>
<td>3.2 mm²</td>
</tr>
<tr>
<td>Dec 97</td>
<td>12</td>
<td>10MS/s</td>
<td>0.2LSB</td>
<td>335mW</td>
<td>continuously calibra. pipelined, 0.5um</td>
<td>&quot;A Single Ended 12b 20MS/s Self-Calibrating Pipelined ...&quot;</td>
<td>3.7 mm²</td>
</tr>
<tr>
<td>Dec 98</td>
<td>12</td>
<td>400MS/s</td>
<td>0.9LSB</td>
<td>200mW</td>
<td>folding</td>
<td>digital telecommunication digital imaging</td>
<td>1.8 mm²</td>
</tr>
<tr>
<td>Dec 98</td>
<td>6</td>
<td>400MS/s</td>
<td>0.9LSB</td>
<td>200mW</td>
<td>pipelined</td>
<td>&quot;A Continuously Calibrated 12b 10MS/s 3.3V ADC&quot;</td>
<td>1.8 mm²</td>
</tr>
<tr>
<td>Jul 98</td>
<td>10</td>
<td>40MHz</td>
<td></td>
<td>230mW</td>
<td>Pipelined</td>
<td>LAN, hard disk drive read channels &amp; communication circuits</td>
<td>2.5 mm²</td>
</tr>
<tr>
<td>Jul 98</td>
<td>15</td>
<td>40MHz</td>
<td></td>
<td>230mW</td>
<td>Pipelined</td>
<td>&quot;A 400MS/s 6b CMOS Folding and Interpolating ADC&quot;</td>
<td>2.5 mm²</td>
</tr>
<tr>
<td>May 99</td>
<td>10</td>
<td>14.3MS/s</td>
<td>0.5LSB DN1, 0.7 LSB INL</td>
<td>36mW</td>
<td>Pipelined 0.8um</td>
<td>1um Fully differential switched cap. Circuits</td>
<td>2.3 mm²</td>
</tr>
</tbody>
</table>

Table A.10
<table>
<thead>
<tr>
<th>Year</th>
<th>Bit</th>
<th>Sampling Rate</th>
<th>Linearity</th>
<th>Power</th>
<th>Architecture</th>
<th>Applications</th>
<th>Die Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>912</td>
<td>500MS/s</td>
<td>0.32 LSB DNL</td>
<td>225mW</td>
<td>0.35um Full Flash</td>
<td>disk drive read channels</td>
<td>0.8 mm2</td>
</tr>
<tr>
<td>99</td>
<td>15</td>
<td>52.8MHz</td>
<td>&lt;1 LSB DNL</td>
<td>200mW</td>
<td>ΣΔ 0.5um</td>
<td>ADSL, high speed and resolution</td>
<td>5 mm2</td>
</tr>
<tr>
<td>99</td>
<td>6</td>
<td>75MS/s</td>
<td>&lt;1 LSB INL</td>
<td>110mW</td>
<td>Folding 0.5um</td>
<td>&quot;A 3.3V, 15b ΣΔ ADC with a Signal Bandwidth of 1.1MHz ...&quot;</td>
<td>1 mm2</td>
</tr>
<tr>
<td>Aug</td>
<td>992</td>
<td>10</td>
<td>&lt;1 LSB DNL</td>
<td>324mW</td>
<td>Pipelined ΣΔ 1.2um Nyquist Rate</td>
<td>dat commun. &amp; data storage sys. High speed, medium resolution</td>
<td>6 mm2</td>
</tr>
<tr>
<td>99</td>
<td>13</td>
<td>16MHz</td>
<td>&lt;.5 LSB</td>
<td>75mW</td>
<td>Subranging</td>
<td>&quot;A Nyquist Rate Pipelined Sampling ΣΔ AD Converter&quot;</td>
<td>1.6 mm2</td>
</tr>
<tr>
<td>Dec</td>
<td>1777</td>
<td>10</td>
<td>&lt;.4 LSB DNL</td>
<td>75mW</td>
<td>Nyquist cascode Folding &amp; Interpolating boomerangs</td>
<td>&quot;A 75mW 10b 20MS/s CMOS Subranging ADC with 0.5 ...&quot;</td>
<td>0.6 mm2</td>
</tr>
<tr>
<td>99</td>
<td>1788</td>
<td>40MS/s</td>
<td>0.3 LSB DNL</td>
<td>65mW</td>
<td>Nyquist cascode Folding &amp; Interpolating boomerangs</td>
<td>digital communication, video signaling</td>
<td>0.8 mm2</td>
</tr>
<tr>
<td>99</td>
<td>1796</td>
<td>10</td>
<td>0.7LSB DNL</td>
<td>195mW</td>
<td>Two step 0.35um</td>
<td>&quot;A 65mW, 10b 40MS/s BICMOS Nyquist ADC in 0.8um2&quot;</td>
<td>1 mm2</td>
</tr>
<tr>
<td>99</td>
<td>1803</td>
<td>25MS/s</td>
<td>0.9 LSB INL</td>
<td>3.3V</td>
<td>Algorithmic</td>
<td>video, quadrature amplifier modulation, digital television</td>
<td>5.5 mm2</td>
</tr>
<tr>
<td>99</td>
<td>1812</td>
<td>125kS/s</td>
<td>0.34 LSB DNL</td>
<td>15mW</td>
<td>1.5um</td>
<td>&quot;A 3.3V, 10b, 25MS/s Two-stage ADC in 0.35um CMOS&quot;</td>
<td>5.5 mm2</td>
</tr>
</tbody>
</table>

Table A.11
APPENDIX B

COMPLETE CIRCUIT SCHEMATICS and MASK LAYOUTS
1. Complementary-Input Voltage Comparator

Figure B.1 Voltage comparator circuit schematic.

<table>
<thead>
<tr>
<th>DEVICE LABEL</th>
<th>ASPECT RATIO (μm / μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 / M2</td>
<td>1 / 0.18</td>
</tr>
<tr>
<td>M3 / M4</td>
<td>1 / 0.18</td>
</tr>
<tr>
<td>M5 / M6</td>
<td>2 / 0.18</td>
</tr>
<tr>
<td>M7 / M8</td>
<td>5 / 0.18</td>
</tr>
<tr>
<td>M9 / M10</td>
<td>3 / 0.18</td>
</tr>
<tr>
<td>M11 / M12</td>
<td>3 / 0.18</td>
</tr>
<tr>
<td>M13 / M14</td>
<td>2 / 0.18</td>
</tr>
<tr>
<td>M15 / M16</td>
<td>5 / 0.18</td>
</tr>
<tr>
<td>M17</td>
<td>10 / 0.18</td>
</tr>
</tbody>
</table>

Table B.1 Voltage comparator transistor dimensions.
Figure B.2 Mask layout of the improved complementary input voltage comparator.

Silicon area is approximately 132 $\mu\text{m}^2$. 
2. OTA-Based Operational Amplifier

![Circuit Diagram]

Figure B.3 OTA based op-amp circuit schematic.

<table>
<thead>
<tr>
<th>DEVICE LABEL</th>
<th>ASPECT RATIO (µm / µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1 / M2</td>
<td>10 / 0.5</td>
</tr>
<tr>
<td>M3 / M4</td>
<td>0.36 / 0.18</td>
</tr>
<tr>
<td>M5 / M6</td>
<td>3.6 / 0.18</td>
</tr>
<tr>
<td>M7 / M8</td>
<td>2 / 0.18</td>
</tr>
<tr>
<td>M9</td>
<td>7.2 / 0.18</td>
</tr>
<tr>
<td>M10</td>
<td>18 / 0.18</td>
</tr>
<tr>
<td>R_f</td>
<td>50 kΩ</td>
</tr>
<tr>
<td>C_f</td>
<td>100 fF</td>
</tr>
</tbody>
</table>

Table B.2 Op-amp transistor dimensions.
Figure B.4 Mask layout of the OTA based op-amp used as residue amplifier.
Silicon area is approximately 2230 $\mu m^2$. 
3. D-Type Flip Flop (DFF)

Figure B.5 Schematic of two stage master-slave rising edge triggered D-type flip-flop.

<table>
<thead>
<tr>
<th>MOS NAME</th>
<th>ASPECT RATIO (μm / μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M4, M9, M10, M20</td>
<td>1.5 / 0.18</td>
</tr>
<tr>
<td>M6, M16</td>
<td>1 / 0.18</td>
</tr>
<tr>
<td>M13, M19</td>
<td>0.76 / 0.18</td>
</tr>
<tr>
<td>M3, M7, M8, M14, M15, M17</td>
<td>0.5 / 0.18</td>
</tr>
<tr>
<td>M1, M5</td>
<td>0.3 / 0.18</td>
</tr>
<tr>
<td>M2, M11, M12, M18</td>
<td>0.28 / 0.18</td>
</tr>
</tbody>
</table>

Table B.3 DFF transistor dimensions.
Figure B.6 Layout view of the designed type flip-flop.

Silicon area is approximately 132 μm².
4. One-bit Full Adder

Figure B.7 Schematic view of the designed full adder circuit.

<table>
<thead>
<tr>
<th>DEVICE LABEL</th>
<th>ASPECT RATIO ($\mu$m / $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M6, M7, M10</td>
<td>0.76 / 0.18</td>
</tr>
<tr>
<td>M3, M4, M5, M11, M12, M20, M21, M22, M23, M24</td>
<td>0.5 / 0.18</td>
</tr>
<tr>
<td>M8, M9</td>
<td>0.4 / 0.18</td>
</tr>
<tr>
<td>M1, M2, M13, M14, M15, M16, M17, M18, M19, M24, M25, M26</td>
<td>0.28 / 0.18</td>
</tr>
<tr>
<td>M27</td>
<td>/ 0.18</td>
</tr>
<tr>
<td>M28</td>
<td>/ 0.18</td>
</tr>
</tbody>
</table>

Table B.4 Full adder transistor dimensions.
Figure B.8 Layout view of the designed 1-bit full adder circuit.

Silicon area is approximately 107 µm².
5. XOR Gate

![XOR Gate Diagram]

Figure B.9 Schematic view of the designed exclusive-OR (XOR) gate.

<table>
<thead>
<tr>
<th>MOS NAME</th>
<th>ASPECT RATIO (μm / μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1, M2, M3, M4</td>
<td>0.35 / 0.18</td>
</tr>
<tr>
<td>M5, M6, M7, M8</td>
<td>1.05 / 0.18</td>
</tr>
</tbody>
</table>

Table B.5 XOR gate transistor dimensions.
Figure B.10 Layout view of the designed exclusive-OR (XOR) gate.

Silicon area is approximately 45 $\mu$m$^2$. 
Figure B.11 Simplified schematic view of 4-bit thermometer-to-binary encoder.
Figure B.12 Layout view of 4-bit thermometer to binary encoder.
Silicon area is approximately $3126 \, \mu m^2$. 
BIBLIOGRAPHY


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