FPGA Implementation of Codec Design for Optimal Code Rate Crosstalk Avoidance Codes

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Abstract: In deep submicron (DSM) technology, the coupling capacitance is comparable to or exceeds the self or substrate capacitance, which in turn causes the delay of a transition in a wire to be twice or more than that of a wire transitioning next to a steady signal. In this paper, the authors propose a new coding technique which minimizes both coupling and self transition activities in the bus lines using the CODEC design of all classes of CACs based on binary mixed-radix numeral systems and spatial redundancy respectively. Using this framework, we then propose novel CODEC designs for three important classes of CACs; one lambda codes (OLCs), FPCs, and forbidden overlapping codes (FOCs). Our CODEC designs have area complexity and delay that increase quadratically with the size of the bus, while achieving optimal or nearly optimal code rates. Using an FPGA kit we can observe the CACs results on it.

Keywords: CODEC, crosstalk avoidance codes (CACs), interconnect, numeral systems, FPGA kit

1. Introduction

The advancement of very large scale integration (VLSI) technologies has been following Moore’s law for the past several decades: the number of transistors on an integrated circuit is doubling every two years and the channel length is scaling at the rate of 0.7/3 years. It was not long ago when VLSI design marched into the realm of Deep Submicron (DSM) processes, where the minimum feature size is well below 1μm. These advanced processes enable designers to implement faster, bigger and more complex designs. With the increase in complexity, System on Chip (SoC), Network on Chip (NoC) and Chip-level Multiprocessing (CMP) based products are now readily available commercially. In the meanwhile, however, DSM technologies also present new challenges to designers on many different fronts such as (i) scale and complexity of design, verification and test (ii) circuit modelling and (iii) processing and manufacturability.

As VLSI technology has marched into the deep submicrometer (DSM) regime, new challenges are presented to circuit designers. As one of the key challenges, the performance of bus based interconnects has become a bottleneck to the overall system performance. In large designs [e.g., systems-on chip (SoCs)] where long and wide global busses are used, interconnect delays often dominate logic delays. Once negligible, crosstalk has become a major determinate of the total power consumption and delay of on-chip busses. The impact of crosstalk in on-chip busses has been studied as part of the effort to improve the power and speed characteristics of the on-chip bus interconnects. Fig. 1 illustrates a simplified on-chip bus model with crosstalk. Denotes the CL load capacitance seen by the driver, which includes the receiver gate capacitance and also the parasitic wire-to-substrate parasitic capacitance Ci is the inter-wire coupling capacitance between Adjacent signal lines of the bus, In practice, this bus structure is electrically modelled using a distributed resistance-capacitance (RC) network, after including the parasitic resistance of the wire as well (not shown in Fig. 1). For DSM processes, is much greater than [7]. Based on the energy consumption and delay models given in [1], the energy consumption is a function of the total crosstalk over the entire bus. The delay, which determines the maximum speed of the bus, is limited by the maximum crosstalk that any wire in the bus incurs. It has been shown that reducing the crosstalk can boost the bus performance significantly [1], [5].

Since the crosstalk delay is the major part of the delay, different solutions have been proposed to reduce it, e.g. skewing the timing of signals on the bus [2], bus interleaving, pre charging, or using repeaters. These solutions have varying degrees of success. Unfortunately, these solutions are often technology-dependent, power consuming, or susceptible to process variation. A technology-independent solution to this problem is shielding, which cuts the worst case crosstalk delay by half, but it nearly doubles the wiring area; hence it is unattractive since the routing resource on a chip is scarce.

Although most CACs in the literature require less area and power overhead due to wires than shielding, extra logic
Researchers have made a lot of effort in finding an efficient way to implement the CODEC of CACs, leading to solutions such as partial coding [8]. In partial coding, a bus is first broken into sub-buses, which are encoded by using CACs with smaller sizes; then a shielding wire is inserted between each pair of adjacent sub-buses to avoid transition patterns with long crosstalk delay. Forbidden transition overlapping codes (FTOCs) and forbidden pattern overlapping codes (FPOCs) [7] combine partial coding with FTCs and FPCs, respectively. At the expense of a lower code rate and hence larger area and power consumption for the bus, partial coding reduces the complexities of CODECs by keeping the numbers of wires in sub-buses small.

Recently, CODECs based on a Fibonacci based numeral system (FNS) have effectively solved the complexity problem for FPCs and FTCs [10], [11]. Two FPC CODEC designs are proposed based on an FNS [11], and both CODECs have quadratic complexities with the size of the bus. One CODEC in [11] is suboptimal due to its potentially lower code rate, but has a simpler CODEC; the other CODEC in [11] is optimal in its code rate, but requires a more complex circuit. In [10], the FNS is used to encode FTCs. All CODECs in [10] and [11] have quadratic complexities.

In this paper, we generalize the idea in [10] and [11] and establish a generic framework for the CODEC design of all classes of CACs based on binary mixed-radix numeral systems. Using this framework, we propose CODECs for OLCs and FPCs with optimal code rates as well as CODECs for FOCs with near-optimal code rates. Our implementation results show that all our CODECs in this paper have area complexity and delay that increase quadratically with the number of wires and a new coding technique which minimizes self transition activities in the bus lines using spatial redundancy. Our main contributions are as follows.

- In Section 4, generalizing the idea in [10] and [11], we propose a generic encoding algorithm for CACs based on numeral systems.
- In Section 5, we define a modified Fibonacci numeral system, and propose an FPC CODEC based on it. Our FPC CODEC achieves the same code rate as the optimal FPC CODEC in [11] and has a simple circuit, similar to the near-optimal FPC CODEC in [11], integrating the advantages of the two FPC CODECs in [11].
- In Section 6, we define a numeral system for OLC CODECs, and propose an OLC encoding algorithm based on this numeral system. Our CODEC also has a quadratic complexity, which are novel to the best of our knowledge.
- In Section 7, we first prove that we cannot use the generic CAC encoding algorithm based on numeral systems to encode to the whole codebook of an FOC with maximal size. Then we propose an encoding algorithm based on a numeral system that encodes to a subset of an FOC with maximal size. For small, the code rate loss of our suboptimal encoder is small. Our FOC CODECs are also novel to the best of our knowledge. In section 8, the proposed self transition coding scheme is explained, while the results and discussions are provided in section 9 and conclusions are made in section 10.

1.1 Definitions

- Coupling Transition (CT): A Coupling Transition is defined as a transition from 0 – 1 or 1 - 0, between two adjacent bus wires.
- Self Transition (ST): A Self Transition is defined as a transition from 0 -- 1 or 1 - 0 on buses with reference to the previous data on it.
- Bus Width (BW): The number of bits in the data is called the Bus Width.

2. Literature Survey

To address interconnect delay effect cross talk avoidance CODEC’s are best example, they plays a key role in data transmission and reception.

2.1 Introduction of CODEC’s

A codec is a device or computer program capable of encoding or decoding a digital data stream or signal. The word codec is a portmanteau of "coder-decoder" or, less commonly, "compressor- de compressor". A codec encodes a data stream or signal for transmission, storage or encryption, or decodes it for playback or editing. Codec’s are used in videoconferencing, streaming and editing applications.
2.2 Cross talk

Crosstalk (XT) is any phenomenon by which a signal transmitted on one circuit or channel of a transmission system creates an undesired effect in another circuit or channel. Crosstalk is usually caused by undesired capacitive, inductive, or conductive coupling from one circuit, part of a circuit, or channel, to another.

Cross talk leads cross talk delay and cross talk noise which degrade the system performance and May it leads to functionality failure respectively. When two nets are in parallel (one is aggressor and other one is victim) passing the data in the same direction leads to reduced delay of bus and when passing the data in opposite direction leads to increased delay of bus. Similarly when aggressor is switching and victim is static, cross talk noise is introduced between two net which leads to functionality failure of the design.

3. Previous Work

Despite the availability of the codes, no systematic mapping of data words to code words has been proposed for CODEC design. This is mainly due to the nonlinear nature of the crosstalk avoidance codes (CAC). The lack of practical CODEC construction schemes has hampered the use of such codes in practical designs. This work presents guidelines for the CODEC design of the “forbidden pattern free crosstalk avoidance code” (FPF-CAC). We analyze the properties of the FPF-CAC and show that mathematically, a mapping scheme exists based on the representation of numbers in the Fibonacci numeral system. Our first proposed CODEC design offers a near-optimal area overhead performance. An improved version of the CODEC is then presented, which achieves theoretical optimal performance. We also investigate the implementation details of the CODECs, including design complexity and the speed. Optimization schemes are provided to reduce the size of the CODEC and improve its speed.

4. Generic CAC Codec Designs Based On Numeral Systems

4.1 Introduction to Numeral Systems

A numeral system is a linguistic system and mathematical notation for representing numbers of a given set by symbols in a consistent manner [13]. The most commonly used numeral systems are positional numeral systems [13], where given a positive natural number, a string \( \sum_{i=0}^{m} a_i \) represents a number \( \sum_{i=1}^{m} a_i \). For example, the binary and decimal numeral systems use powers of two and powers of ten, respectively, as bases. A binary mixed-radix numeral system is that given a basis set of non-negative numbers \( \{ f_1, f_2, f_3, \ldots, f_n \} \), a binary string \( (d_{m-1} \ldots d_1 d_0) \) represents a number \( \sum_{i=0}^{m} a_i \). In this paper, we focus on binary mixed-radix numeral systems hence forth.

A numeral system is complete if any integer \( a \in [0, 2^k-1] \) can be represented by at least one binary string \( (d_{m-1} \ldots d_1 d_0) \).

4.2 Generic CAC Encoding Algorithm

Suppose we want to transmit a -bit data message over a bus. With \( m(m=0) \) wires in one clock cycle. These k bits are first encoded into an -bit CAC codeword so that the transition patterns with long crosstalk delays are avoided. The k-bit CAC codeword is then transmitted over the bus and received by the decoder. Then the -bit message is recovered at the decoder. The idea of numeral system based CAC CODEC is that the k-bit data message can be viewed as an integer v such that \( 0 \leq v \leq 2^k - 1 \) in the binary numeral system, and the goal of encoding algorithm is to convert into an -bit binary string, which represents under another numeral system and has no transition pattern with...
long crosstalk delay. Since the encoded codeword contains only 0 and 1 and the numeral system needs to be complete, we have to use a binary mixed-radix numeral system.

Consider an m-bit CAC codebook \( C_m \) with size \( C_m \). If a numeral system is used to encode, we consider an encoder, which is essentially a mapping from all integers in \( \mathbb{Z} \) to with the following properties:

- All the codeword’s can be mapped from an integer in, which implies that is subjective;
- Different codeword’s represent different integers under the mapping.

We propose a generic CAC encoding algorithm based on a numeral system in Algorithm 1 below. In Algorithm 1, \( \{r_m, \ldots, r_2, r_1\} \) is the basis set of the encoding numeral system, \( \{\alpha_k, \beta_k\} \) and \( \theta \) are some constants depending on the CACs. \( d_m, d_{m-1}, \ldots, d_2, d_1 \) is the output of the encoding algorithm; also it is a codeword in the CAC. It is easy to see that the data message is recovered by computing

\[
v = \sum_{i=1}^{m} r_i \cdot \gamma_i.
\]

The CODEC for a CAC based on Algorithm 1 is shown in Fig. 1. The encoder consists of processing elements, and all processing elements have the same circuit, shown in Fig. 2. The top processing element is slightly different from the others in that \( d_m = \beta_m = \theta \), which renders the input \( d_{m-1} \) to the top processing element is don’t care (Fig. 1).

Each processing element consists of two comparators, one subtractor, and one multiplexer. Each processing element has three parameters \( \alpha_k, \beta_k \) and \( r_k \), two inputs \( d_{k+1} \) and \( r_{k+1} \), and two outputs \( d_k \) and \( r_k \).

**Algorithm 1 Generic CAC encoding algorithm**

**Input:** code length \( m \), integer \( v (0 \leq v \leq \sum_{i=1}^{m} \gamma_i) \)

For \( k = m \) downto 2 do

if \( k = m \) then

if \( v \geq \theta \) then

\( d_m = 1; \)

else

\( d_m = 0; \)

end if

\( r_m = v - d_m \cdot \gamma_m; \)

else

if \( r_{k+1} \geq \alpha_k \) then

\( d_k = 1; \)

else if \( r_{k+1} < \beta_k \) then

\( d_k = 0; \)

else

\( d_k = d_{k+1}; \)

end if

\( r_k = r_{k+1} - d_k \cdot \gamma_k; \)

end if

end for

\( d_1 = r_2; \)

**Output:** \( d_m, d_{m-1}, \ldots, d_1 \).

**Figure 3.1:** Generic CODEC of an m-bit CAC based on Algorithm 1 (note the similarity to the CODEC shown in [11, fig.3]. a) Encoder. b) Decoder.

**Figure 3.2:** Processing element of the encoder in fig.1 (note the similarity to [11, fig.4].

5. Forbidden Pattern Free CAC

FPC is familiar to avoid \((1+2^\lambda)\) codes. The codebook size of an m-bit FPC is given by \(2F_m+1\), slightly greater than that of an m-bit FTC. Since the number of codeword’s needed is a power of two, an m-bit FPC leads to a higher rate than an m-bit FTC.

5.1 Numerical systems for FPC Codec’s

Let \( \{F_k\} \) be a Fibonacci sequence. We have the following proposition.

**FPC CODEC Design**

With the help of the MFNS, the FPC CODEC can be designed as a special case of our general CAC by choosing

\[
\gamma_k = P_k, \quad \theta = F_m + 1, \quad \alpha_k = F_{k+1}, \quad \beta_k = F_K.
\]

**Generic CAC encoding algorithm:**

**Input:** code length \( m \), integer \( v (0 \leq v \leq \sum_{i=1}^{m} \gamma_i) \)

For \( k = m \) downto 2 do

if \( k = m \) then

if \( v \geq \theta \) then

\( d_m = 1; \)

else

\( d_m = 0; \)

end if

\( r_m = v - d_m \cdot \gamma_m; \)

else

if \( r_{k+1} \geq \alpha_k \) then

\( d_k = 1; \)

else if \( r_{k+1} < \beta_k \) then

\( d_k = 0; \)

else

\( d_k = d_{k+1}; \)

end if

\( r_k = r_{k+1} - d_k \cdot \gamma_k; \)

end if

end for

\( d_1 = r_2; \)

**Output:** \( d_m, d_{m-1}, \ldots, d_1 \).
else
dm=0;
endif
rm=v-dm.ym;
else
if rk+1 ≥ ak then
dk=1;
elseif rk+1 < βk then
dk=0;
else
dk=dk+1;
end if
rk=rk+1- dk.yk;
end if
end for
d1=r2;
output: dm.dm-1.dm-2.d…..d1

As a special case of our generic CAC CODEC, the circuitry
of our FPC CODEC design has a quadratic complexity.

The below table represent FPF-CAC code words for 2, 3, 4
and 5-bit buses.

<table>
<thead>
<tr>
<th>2-bit</th>
<th>3-bits</th>
<th>4-bits</th>
<th>5-bit</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>000</td>
<td>0000</td>
<td>10000</td>
</tr>
<tr>
<td>01</td>
<td>001</td>
<td>0001</td>
<td>10001</td>
</tr>
<tr>
<td>10</td>
<td>011</td>
<td>0011</td>
<td>10111</td>
</tr>
<tr>
<td>11</td>
<td>100</td>
<td>0110</td>
<td>11000</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>0111</td>
<td>11011</td>
</tr>
<tr>
<td></td>
<td>111</td>
<td>1000</td>
<td>11100</td>
</tr>
<tr>
<td></td>
<td>1001</td>
<td>01110</td>
<td>11110</td>
</tr>
<tr>
<td></td>
<td>1100</td>
<td>01111</td>
<td>11111</td>
</tr>
<tr>
<td></td>
<td>1110</td>
<td>1110</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1111</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. One lambda codes (OLC)

The \((1+λ)T0\) codes can achieve a worst case delay of
\((1+λ)T0\) OLCs, are a kind of \((1+λ)\) codes. In an OLC, no
adjacent wires can transition in opposite directions when
transitioning from one codeword to another. Thus the
transition patterns 01 \(→\) 10 and 10 \(→\) 01 are avoided.
Consider a boundary between two adjacent wires. If in all
codeword’s, there are only 00, 01, and 11 across this
boundary, it is referred to as 01-type boundary. Otherwise if
only 00, 10, and 11 appear this boundary, it is referred to as a
10-type boundary. All of the boundaries in an OLC are either
01-type or 10-type. That the OLC codebook with maximal
size satisfies the following two conditions: 1) The codebook
has alternating 01- and 10-type boundaries and 2) the bit
patterns 010, 101, 1001, and 0110 cannot appear in any of
the codeword’s. The maximal cardinality of an m-bit OLC
codebook is given by \(g_m\). The numeral system defined by
\(\{f_i\}i=1m\) can be used to encode an m-bit OLC.

\[γ_k = f_k, \quad Θ=G2[m/2]+4\]
\[α_k = G2l+2, \quad \text{for } k=2l-1 \text{ and infinity for } k=2l\]
\[β_k = 0, \quad \text{for } k=2l-1 \text{ and } G2l+2 \text{ for } k=2l-1\]

6.2 OLC CODEC Design

Generic CAC encoding algorithm:

Input: code length \(m\), integer \(v\) (\(0≤v≤\sum_{i=1}^{m} γ_i\))

For \(k=m\) down to 2
do if \(k=m\) then
if \(v≥θ\) then
\(dm=1\);
else
\(dm=0\);
endif
\(rm=v-dm.ym\);
else
if \(rk+1 ≥ α_k\) then
\(dk=1\);
elseif \(rk+1 < β_k\) then
\(dk=0\);
else
\(dk=dk+1\);
end if
\(rk=rk+1-dk.yk\);
end if
end for
\(d1=r2\);
output: dm.dm-1.dm-2.d…..d1

The bit patterns 1001 and 0110 violate the alternating
boundary type constraint, and thus they cannot appear in the
output vector. Thus the output vector is an OLC codeword.
Since the largest codebook size of an -bit OLC is\(, and we
can get different codeword’s satisfying the constraints of
OLC codeword’s by the OLC encoding algorithm, the
algorithm gives a bisection from integers in to the -bit OLC
codebook, implying that the algorithm is optimal.

The One lambda codes efficiently work and yield good
codec designs based on data bit transitions by making data
transition in one direction as mentioned in introduction of
one lambda codes.

6.1 Numeral systems for OLC Codec’s

The OLC’s codec can be designed by choosing the following
parameters the maximal cardinality of an m-bit OLC

gm= gm-1 + gm-5 \text{ for } m≥6
7. Forbidden Over Lapping Codes (FOC)

The \((1+3\lambda)T0\) codes can achieve a worst case delay of \((1+3\lambda)T0\) FOCs, are a kind of \((1+3\lambda)\) codes. A 3-bit pattern \(b1b2b3\) around a bit \(d_i\) if \(d_i+1d_id_i-1 = b1b2b3\). The FOC codebook satisfies the following constraint: the codebook cannot have both 010 and 101 appearing around any bit position. The maximal size of an \(m\)-bit FOC is given by, \(T_m\)

\[ T_m = T_{m-1} + T_{m-2} + T_{m-3} \]

for \(m \geq 4\) and \(T_1 = 2\), \(T_2 = 4\), and \(T_3 = 7\).

Generic CAC encoding algorithm:

Input: code length \(m\), integer \(v\) (0 ≤ \(v\) ≤ \(\sum_{i=1}^{m} \gamma_i\))

For \(k = m\) downto 2

do if \(k = m\) then

if \(v \geq \alpha_k\) then

\(d_m = 1\);  
\(r_m = v - d_m \cdot \gamma_m\);  
else

\(d_m = 0\);  
end if

end if

else

if \(r_k+1 \geq \beta_k\) then

\(d_k = 1\);  
elseif \(r_k+1 < \beta_k\) then

\(d_k = 0\);  
else

\(d_k = d_k + 1\);  
end if

end if

\(d_1 = 2\);  
output: \(d_md_m-1d_m-2d_\ldots d_1\)

The processing element for FOC CODEC is shown in the following figure 3.4.

8. Self Capacitance Reduction

A self capacitance is defined as the Capacitance associated with the net and body or substrate of the device. A common form of energy storage device is a parallel-plate capacitor. In a parallel plate capacitor, capacitance is directly proportional to the surface area of the conductor plates and inversely proportional to the separation distance between the plates.

The self capacitance reduction is done by comparing the present input with previous input and selecting appropriate encoded data pattern corresponding to the minimum value of self transitions is transmitted on the bus.

Self capacitance reduction is done by the following procedure.

Let the data on an \(n\) bit wide bus, at time instant to be denoted as \(A_t = \{a_{t_n-1}, a_{t_n-2}, a_{t_n-3}, \ldots, a_{t_1}, a_{t_0}\}\). The data transmitted on the bus is denoted as \(A(t)\) enc. The function calculates (data1, data2) finds the number of self transitions between (data1, data2). The function swapAdj_n (At) swaps the adjacent bus lines in At and gives the output Asw(t) = \{a_{t_n-1},a_{t_n-2},a_{t_n-3},\ldots,a_{t_0},a_{t_1}\}.

The energy efficient coding scheme is as follows:

- Let \(A(t-1)\)enc be the previously coded data which was transmitted on the bus and let \(At\) be the present data which should be encoded and transmitted.
- Find XOR of \(At\) with \(A(t-1)\)enc and affix it with 00, for decoding purposes. Let this new data be denoted as \(At(xor)\). Evaluate \(stxor=calculateST_n(At(xor), A(t-1)\)enc\).
- Likewise, find XNOR of in \(At\) with \(A(t-1)\)enc and affix it with 01. Let this new data be denoted as \(At(xnor)\). Evaluate \(stxnor=calculateST-n(At(xnor), A(t-1)\)enc\).
- Let \(Asw(t)\) = swapAdj_n(At). Suffix ASW (t) with 01 and let this new data be denoted as \(At(swP)\).
- Evaluate \(stswp=calculateSTLn(At(swP), A(t-1)\)enc\).
- Suffix \(At\) with 11 and let this new data be denoted as \(At(unc)\). Evaluate \(stunc=calculateST-n(At(unc), A(t-1)\)enc\).
- Find min (\(stLxor, stxnor, stswp, stunc\)).
- The coded value corresponding to the minimum value in step six is transmitted.

The block diagram for self capacitance reduction encoder is depicted as.
Figure 4.2: Self capacitance reduction encoder

The block diagram for self capacitance reduction decoder is depicted as

Figure 4.3: Self capacitance reduction decoder

9. Results and Discussion

Comparison of different CAC’s

The following table 3.3 depicts the constants which are used in different CAC’s

<table>
<thead>
<tr>
<th>CAC</th>
<th>Path delay (ns)</th>
<th>Power Req. (mw)</th>
<th>No. of slices (out of 8672)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPC</td>
<td>41.760</td>
<td>152.43</td>
<td>52</td>
</tr>
<tr>
<td>OLC</td>
<td>45.546</td>
<td>158.02</td>
<td>48</td>
</tr>
<tr>
<td>FOC</td>
<td>56.975</td>
<td>148.43</td>
<td>77</td>
</tr>
</tbody>
</table>

The delay of different CAC’s is represented in the figure 4.4

Figure 4.4: Delay comparison of different CAC’s
To quantify the delay as well as area and power overheads introduced by our CAC CODECs, we implemented our OLC, FPC, and FOC CODECs based on numeral systems without pipelining. Our CODECs are simulated on Modelsim2 and synthesized by Cadence Encounter RTL Compiler3 with an OKSU Free PDK 45-nm process 4; the figures for power consumption of our CODECs are derived by the power analysis tool in Encounter.

To measure the CODEC power consumption, we assume the clock rate is 100 MHz and set the input switching rate to be 0.5 for all CODECs. The clock rate is selected merely for the purpose of demonstrations, and is inconsequential to our conclusions below. In practice, the clock rate should be determined by bus delays as well as CODEC delays. Our CODEC delays are not likely to be the bottleneck of achievable clock rates for two reasons. First, the delays of our CODECs can be easily improved by pipelining or partitioning the bus, as discussed in the paper. Second, since the technology trend indicates increasing bus delays and decreasing gate delays, the bus delays will be more likely to be the bottleneck.

The implementation results are shown in Figs. 4–4. Fig. 4.5 shows the delay introduced by our CODECs, CODEC complexities in terms equivalent gate count. The result of area consumption includes the cell area only. The power consumption of our CODECs, include the leakage power and the estimated internal and switching power. Our simulation results show that the delay and the area complexity as well as the power consumption of our CODECs increase quadratically with the bus width.

10. Conclusion

In this paper, we establish a framework for the CAC CODEC design based on numeral systems, and devise efficient CODECs for OLCs, FPCs, and FOCs by choosing appropriate numeral systems and constants. The results are summarized in Table I. Implementation results show that our CODECs all have area and delay that increase quadratically with the bus width. Used together with partial coding, our efficient CODECs help make CACs a viable option in combating crosstalk delay, which is a bottleneck in deep sub-micron system-on-chip designs.

11. Future work

The analytical models and noise reduction techniques were analyzed for use with past, present, and future IC packaging in order to predict and improve performance. The experimental results illustrated that the techniques were successful and made significant improvement in the performance of the pack- aging. While these techniques were demonstrated to have an immediate impact when applied to commonly used VLSI packages, the current trends in IC technology make these techniques even more invaluable. In addition, since all of the modelling and performance techniques were described using a common mathematical framework, the work in this monograph can be easily applied to a wide variety of electronic applications.

References

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