Thermometer-to-binary Encoder with Bubble Error Correction (BEC) Circuit for Flash Analog-to-Digital Converter (FADC)

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Abstract — Thermometer-to-binary (TM2B) encoder is an important component of a Flash Analog-to-Digital Converter (FADC). Bubble error, extremely often, effects the correction of TM2B as well as high speed sampling rate. In this paper, we propose a MUX-based TM2B circuit that can correct bubble errors. Error correction ability of our proposed circuit is compatible with previous methods. The simulation results show that the proposed circuit requires a small number of transistors and consumes low power.

Keywords: Thermometer-to-binary Encoder, Bubble Error Correction Circuit (BEC), Flash ADC

I. INTRODUCTION

As a result of development of storage system, optical communication, and ultra-wideband communication, the demand for high-speed analog to digital converter (ADC) has being increased [1]. Among different ADC architectures, flash ADC offers the highest sampling rate with low resolution [2]. Until now, flash ADC is the only architecture satisfying the high sampling rate requirement of those areas. Many researches are trying to increase sampling rate and reduce power consumption of flash ADC [1], [3], [4].

Despite of different specific design, general structure of a flash ADC includes three components as shown in Figure 1. The first component is a resistor ladder that provides $2^n - 1$ voltage references, which are divided into equally space values, for an $n - output$ flash ADC. The second component is a set of $2^n - 1$ comparators. Each comparator compares input voltage and referenced voltage. Output of a comparator is digital value 1 if input voltage is higher than referenced voltage. The $2^n - 1$ outputs of comparators always have the form of a thermometer code. The last component is a TM2B digital circuit converting $2^n - 1$ input thermometer code to $n - output$ binary code.

The straightforward method to implement TM2B circuit is to use a binary-encoded ROM [5], [6]. Another method counts the number of bit 1 in thermometer code by a Wallace tree counter [7]. Later, a method use a logic gate based on fat-tree is proposed [8]. Recently, E. Sial and M. Vesterbacka proposed a method based on multiplexer [9].

A review shows that MUX-base circuit has many advantages such as chip area, power consumption [10].

Because flash ADC operates at very high speed, bubble error — there are one or some logical 1 above sequence of logical 0 in thermometer code — will happen. Bubble error is result of many sources, for example, clock jitter, device mismatch, offset voltage. The input thermometer code of a TM2B circuit is invalid code. Consequently, if there is no correction circuit, the output of the TM2B circuit or the output of the ADC in this case is incorrect.

Wallace-tree method can reduce all bubble errors. Unfortunately, this method is not suitable for practical ADC due to the complexity of the circuit, high power consumption, and relatively low speed. ROM-based and fat-tree TM2B circuits use 3-input AND gate to correct bubble error [5], [8]. N. Agrawal and R. Paily propose an improvement for bubble error correction of ROM-base TM2B encoder [11]. Although MUX-based encoder has many advantages, no research proposes a bubble error correction (BEC) circuit for it.

![Figure 1. Structure of Flash ADCs](image-url)
In this paper, we propose a MUX-based TM2B encoding with BEC circuit. Analysis shows that the proposed circuit has the same error correction ability as ROM-based and fat-tree circuit. Circuit design and simulation with Cadence’s tool shows that the proposed circuit not only requires a small number of transistors but also consumes low power.

The rest of the paper is organized as follow. Section II and Section III discuss the ROM-based and fat-tree TM2B encoder. Section IV presents our proposed circuit. Section V discusses the equivalent functionality of circuits, describes simulation setup and present simulation results. The last section is the conclusion.

II. ROM-BASED TM2B ENCODER

The structure of a ROM-based encoder is shown in Figure 2. The encoder includes two sub-circuits, a thermometer-to-one-hot (TM2OH) sub-circuit and a ROM-based encoding sub-circuit. The TM2OH sub-circuit converts thermometer code to one-hot code. The ROM-based encoding sub-circuit is a ROM circuit that convert input in one-hot code to output in binary code.

TABLE I. illustrates the operation of a 7-to-3 ROM-based TM2B encoder. Each row of the table is a valid input code and its corresponding output at each sub-circuit outputs. As illustrated in the table, the 7-to-3 ROM-based TM2B encoder has 7 inputs and 3 outputs. There are total 8 different valid input codes and 8 corresponding output codes.

\[
OUT_i = IN_i, (IN_{i+1})', \quad i = 1, 2, \ldots, 2^n - 2
\]  

where \( OUT_i \) is the output at the position \( i \) and \( IN_i, IN_{i+1} \) are the input at the position \( i, i+1 \), respectively.

![Figure 2. Structure of ROM-based TM2B Encoder](image)

![Figure 3. TM2OH Sub-circuit of a 7-to-3 ROM-based TM2B Encoder](image)

The TM2OH sub-circuit is implemented by 2-input AND gate which one input is inverted. Figure 3. is the TM2OH sub-circuit of a 7-to-3 ROM-based TM2B encoder. Except the highest significant output, other outputs are determined by below formula

![Figure 4. TM2OH Sub-circuit with BEC of a 7-to-3 ROM-based TM2B Encoder](image)

ROM-based encoding sub-circuit is a ROM-structure circuit without address decoding circuit. The content of ROM

![Figure 5. TM2OH Sub-circuit with BEC of a 7-to-3 ROM-based TM2B Encoder](image)
is the binary value output of the TM2B circuit. It does not need the address decoding circuit because its input is one-hot code which can be used to access ROM structure directly.

The circuit structure presented in above paragraphs cannot handle bubble error. Whenever bubble error happens, the output of the encoder becomes incorrect. This reduces the efficient of the circuit. Therefore, a bubble error correction circuit is often used in ROM-based TM2B encoder.

The BEC circuit in ROM-based encoder is a modified TM2OH sub-circuit. Instead of 2-input AND gate, the BEC circuit uses 3-input AND gate. The new circuit performs the converting and correcting processes simultaneously. The output $i$ can be determined by below equation.

$$\text{OUT}_i = \text{IN}_i \cdot (\text{IN}_i \cdot \text{IN}_{i+1})' \quad i = 1,2,...,2^n - 3 \quad (2)$$

Figure 4. is the BEC circuit for a 7-to-3 ROM-based TM2B encoder. As show in the figure, every output is a AND operation of three inputs where all inputs except lowest input are inverted.

### III. FAT-TREE TM2B ENCODER

The structure of a fat-tree TM2B encoder is shown in Figure 5. Similarly with ROM-based encoder, fat-tree encoder also has two sub-circuits. The first sub-circuit converts thermometer code to one-hot code. The first sub-circuit has the same structure as the TH2OH sub-circuit of ROM-based encoder. The second sub-circuit converts one-hot code to binary code. However, the second sub-circuit has a different structure with ROM-based encoding sub-circuit.

Fat-tree encoding sub-circuit is a logic circuit. With an $2^n - 1$ inputs circuit, each output is an OR operation of $2^{n-1}$ inputs. Equations (3), (4), and (5) are the formulas that convert one-hot code to binary code.

$$b_0 = h_1 + h_3 + h_5 + h_7 \quad (3)$$

$$b_1 = h_2 + h_3 + h_6 + h_7 \quad (4)$$

$$b_2 = h_4 + h_5 + h_6 + h_7 \quad (5)$$

where $b_0, b_1, b_2$ are binary code outputs and $h_1$ to $h_7$ are thermometer code inputs.

Reusing some sub-circuits, the number of OR gates are reduced. Figure 6. is the fat-tree encoding sub-circuit of a 7-to-3 fat-tree TM2B encoder. The OR result of input $h_6$ and input $h_7$ is reused to generate output $b_1$. This structure can be easy to extend to higher number of inputs.

Figure 5. Structure of Fat-tree TM2B Encoders

Because fat-tree TM2B encoder uses TM2OH sub-circuit as ROM-based TM2B encoder, BEC circuit of fat-tree TM2B encoder is identical with the one of ROM-based TM2B encoder.

### IV. PROPOSED CIRCUIT – MUX-BASED TM2B ENCODING WITH BEC CIRCUIT

MUX-based TM2B encoder converts thermometer code to binary code directly. The encoder uses multiplexers as primitive gate to implement converting function. A 7-to-3 MUX-based TM2B encoder is shown in Figure 7. As shown in the figure, the circuit has a high structure. Hence, the circuit can extend to higher input encoder easily.

Figure 6. Fat-tree Encoding Sub-circuit of a 7-to-3 Fat-tree TM2B Encoder

Figure 7. A 7-to-3 MUX-based TM2B Encoder
MUX-based TM2B encoder has many advantages such as low power consumption, low circuit complexity, etc [9], [10]. In previous researches, however, it lacks the BEC ability.

In this research, we propose a MUX-based TM2B encoder that can correct bubble error. The structure of our proposed circuit is shown in Figure 8. The MUX-based TM2B encoder in previous researches becomes the MUX-based encoding sub-circuit in our proposed circuit. A new sub-circuit is added before the MUX-based encoding sub-circuit. The new circuit removes bubble error in thermometer code.

\[
OUT_i = IN_i + IN_{i+1} \quad i = 1, 2, \ldots 2^n - 2
\]  

(6)

Figure 9 is the proposed BEC sub-circuit of a 7-to-3 TM2B encoder. As shown in the figure, a circuit with \(2^n - 1\) inputs requires \(2^n - 2\) 2-input OR gates.

V. DISCUSSION AND SIMULATION RESULTS

Comparing with BEC circuit for ROM-based TM2B encoder, the proposed BEC circuit has the same correction ability. Both circuits can correct single bubble error, i.e. only one input is invalid between two valid inputs. If there are more than one bubble errors, the output of both circuits are still incorrect.

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

With the same functions, the proposed circuit has advantages in circuit complexity and power consumption.

To compare the complexity, three different 63-to-6 TM2B circuits are simulated with Cadence tool. The circuit configuration is shown in Figure 10. Input generator generates value for 63 inputs of tested 63-to-6 TM2B circuits. The input values change from the maximum value to the minimum value. Binary value outputs of TM2B circuits are measured to verify the correction of circuits. Power consumption is monitored in simulating process and reported at the end of the simulating process.

<table>
<thead>
<tr>
<th>Circuits</th>
<th>Transistor requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM-based + BEC circuit</td>
<td>714</td>
</tr>
<tr>
<td>Fat-tree + BEC circuit</td>
<td>832</td>
</tr>
<tr>
<td>MUX-based + proposed BEC circuit</td>
<td>722</td>
</tr>
</tbody>
</table>

To compare the power consumption, three TM2B circuits are simulated with Cadence tool. The circuit configuration is shown in Figure 10. Input generator generates values for 63 inputs of tested 63-to-6 TM2B circuits. The input values change from the maximum value to the minimum value. Binary value outputs of TM2B circuits are measured to verify the correction of circuits. Power consumption is monitored in simulating process and reported at the end of the simulating process.

<table>
<thead>
<tr>
<th>Input with bubble error</th>
<th>TM2OH with BEC</th>
<th>Proposed BEC circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>A B C</td>
<td>A B C</td>
<td>A B C</td>
</tr>
<tr>
<td>0 0 0</td>
<td>0 0 0</td>
<td>0 0 0</td>
</tr>
<tr>
<td>0 0 1</td>
<td>0 1 0</td>
<td>1 0 0</td>
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<td>0 1 0</td>
<td>0 1 0</td>
<td>0 1 1</td>
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Average power consumption of three circuits operating at 500 MHz is shown in Table IV. As shown in the table, ROM-base encoder circuit consumes most power, whereas fat-tree circuit consumes least power. The proposed circuit requires only a little more power than fat-tree circuit.

<table>
<thead>
<tr>
<th>Circuits</th>
<th>Average power consumption (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROM-based + BEC circuit</td>
<td>1.831</td>
</tr>
<tr>
<td>Fat tree + BEC circuit</td>
<td>0.942</td>
</tr>
<tr>
<td>MUX-based + proposed BEC circuit</td>
<td>1.211</td>
</tr>
</tbody>
</table>

TABLE IV. AVERAGE POWER CONSUMPTION OF 6-BIT TM2B ENCODER CIRCUITS AT 500MHZ

TABLE III. and TABLE IV. show that the proposed circuit has a balance between circuit complexity and power consumption.

VI. CONCLUSION

In this paper, we proposed a MUX-based TM2B encoder with BEC circuit. The proposed circuit can correct single bubble error. Circuit simulation shows that the proposed circuit has low circuit complexity and low power consumption. Proposed circuit will be prototyped and tested to verify simulation results in next research.

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