Logical Design of Quaternary Signed Digit Conversion Circuit and its Effectuation using Operational Amplifier

Tanay Chattopadhyay and Tamal Sarkar

Abstract--- In binary number system carry is a major problem in arithmetical operation. We have to suffer $O(n)$ carry propagation delay in n -bit binary operation. To overcome this problem signed digit is required for carry free arithmetical operation. Further, literature reviews suggest that multi-valued logic (MVL) would be a better choice to address the problem of developing faster chips for performing faster computational operation. Quaternary Signed Digit (QSD) have a major contribution in higher radix ($=4$) carry free arithmetical operation. For digital implementation, the signed digit quaternary numbers are represented using 3-bit 2's compliment notation. In this paper, a simple and new technique of binary (2's compliment) to QSD conversion is proposed and described. Well-known operational amplifier (OPAMP) based digital to analog converter circuit is also given to verify the above technique.

Keywords--- Multi-Valued Logic, Binary 2's Compliment Number, Quaternary Signed Digit, Radix Conversion, OPAMP

I. INTRODUCTION

MODERN computers are based on binary number system (radix $=2$). It has two logical states '0' and '1'. In such system, '1' plus '1' is '0' with carry '1' (i.e. $1+1=10$). This carry should have to add with another '1', as a result further carry '1' generates. This creates the delay problem in computer circuits. So to get rid of this carry formation again and again signed digit is essential. In high-speed arithmetical calculation, carry free adders improves the operational performance. Binary logic is restricted to only two logical states; Multi-Valued Logic (MVL) replaces these with finite and infinite numbers of values [1]. Multi-valued logic is a higher radix ($R>2$) logic system. Non-binary data requires less physical storage space than binary data [2-4]. Depending upon the radix number R , the number system are named as ternary ($R = 3$), quaternary ($R = 4$) etc. Ternary logic is based on ternary number system. They can further be divided into two groups; symmetric ternary $\{\bar{1}, 0, 1\}$ and ordinary ternary $\{0,$

1, 2 $\}$. Both groups are important in logical and arithmetical operations [5-8]. Quaternary logic is based on radix-4 number system. In quaternary system, the positive integer set $\{0, 1, 2, 3\}$ is called ordinary quaternary digit (OQD) and the set of both positive and negative integer $\{\bar{3}, \bar{2}, \bar{1}, 0, 1, 2, 3\}$ is called quaternary signed digit (QSD). Where $\bar{3} = -3$, $\bar{2} = -2$, $\bar{1} = -1$. In signed digit representation QSD number can be written as [9]:

$$X = \sum_{i=0}^{n-1} x_i \cdot 4^i ; \text{ where } x_i \in \{\bar{3}, \bar{2}, \bar{1}, 0, 1, 2, 3\} \quad (1)$$

Signed digit representation is essentially required for carry free arithmetic operation. As such, binary to quaternary signed digit conversion is very much interesting and required topics. This is called 'radix conversion'. The importance of radix conversion is shown in flexogram at fig.1.

Ordinary quaternary number can be easily expressed as two bit binary number [10-15]. The implementation of multi-

Figure 1: The Importance of Radix Conversion

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valued logic using ordinary quaternary digit has been studied by using various devices, such as I^2L [16], CCD [10, 17],

CMOS [11, 13-14, 18], ECL [12, 19], ν MOS [20], MESFET [21] in electronics. In these literatures many logic levels had been considered. Mingoto Jr. proposed quaternary logic circuit using traditional TTL logic family where $0\mu A$, $10\mu A$, $20\mu A$ and $30\mu A$ are designated as four logic level [22]. Park et al [20] designed quaternary logic circuit using ν MOS where 0.5V, 1.5V, 2.5V and 3V. Logic levels in Shanbhag et al are 0V, 2V, 4V and 6V respectively [13]. Tanable et al [23] designed redundant MVL circuit using CMOS where they use binary two states 0-0, 0-1, 1-0 and 1-1 as quaternary 0, 1, 2 and 3 states respectively. Datla et al [24] designed quaternary cell based on supplementary symmetrical logic circuit structure (SUSLOC) using FET. They used 0V, 1.1V, 2.2V and 3.3V for four logical states. Lee et al [25] also designed and simulated 4-valued memory with double-gate thin film transistor. Aragaki et al [26] implemented high density multiple-valued content-addressable memory (MVCAM) where 0V, 1.4V, 2.8V and 4.2V are considered as different quaternary logic levels. Khader and Siy proposed multi-valued AB^2 circuit using ν MOS where they also used different voltage levels as quaternary logical states [27-28]. Also some quantum quaternary logic circuits have been proposed by Khan et al [29-30]. To represent 1-digit QSD three bit binary (2 's complement form) is required [31-32]. Although there have many circuits to represents binary to ordinary quaternary conversion in electronics, but no circuit have not been yet proposed to convert binary to QSD number. In this paper, we have mentioned a technique of this conversion as well as proposed a simple technique of n -bit binary-signed number (2 's complement) to QSD number system. We have also designed a prototype of digital to analog converter circuit using operational Amplifier (OPAMP) to verify the technique.

II. TECHNIQUE OF CONVERSION FROM BINARY NUMBER TO QSD NUMBER

1-digit QSD can be represented by one 3-bit binary equivalent as follows [15]:

$$\begin{aligned}\bar{3} &= 101 \\ \bar{2} &= 110 \\ \bar{1} &= 111 \\ 0 &= 000 \\ 1 &= 001 \\ 2 &= 010 \\ 3 &= 011\end{aligned}\quad (2)$$

So to convert n -bit binary data to its equivalent q -digit QSD data, we have to convert this n -bit binary data into $3q$ -bit binary data. To achieve the target, we have to split the 3^{rd} , 5^{th} , 7^{th} bit... i.e. odd bit (from the LSB to MSB) into two portions [34]. But we cannot split the MSB. If the odd bit is 1 then, it is split into 1 & 0 and if it is 0 then, it is split into 0 & 0. An example makes it clear, the splitting technique of a binary number $(1101101)_2$ is shown below:

So we have to split the binary data $(q-1)$ times (as example, for conversion of 2-bit quaternary number, the splitting is 1 time; for converting 3-digit quaternary number the split is 2-times and so on). In each such splitting one extra bit is generated. So, the required binary bits for conversion to its QSD equivalent (n) = (Total numbers of bits generated after divisions) – (extra bit generated due to splitting).

$$\begin{aligned}n &= 3q - \{1 \times (q-1)\} \\ &= (2q+1)\end{aligned}\quad (3)$$

So, number of bits of the binary number should be 3, 5, 7, 9 etc for converting it to its equivalent QSD number. Now every 3-bit can be converted to its equivalent QSD according to the equation (2). The following two examples as given below will help to make the things clear.

- 1) Let $(-155)_{10} = (101100101)_2$ have be converted to its equivalent QSD. ' $(101100101)_2$ ' is 9-bit binary data. Its 3^{rd} bit is 1, 5^{th} bit is 0 and 7^{th} bit is 1. So from the equation (3) we can say that, its QSD equivalent is of 4-digit. Hence according to the splitting technique stated above the binary data can be expressed as follows.

So the QSD equivalent of $(101100101)_2$ is $(\bar{3}211)_4$.

- 2) Let $(49)_{10} = (0110001)_2$ is to be converted to its equivalent QSD. ' $(0110001)_2$ ' is 7-bit binary number. According to the previous discussion the conversion is as follows

So the QSD equivalent of $(110001)_2$ is $(301)_4$.

III. VERIFICATION OF THE ABOVE TECHNIQUE USING ELECTRONIC CIRCUITS

Figure 2(a): Single-Digit QSD Converter Circuit

It is possible to design One-digit QSD converter by using operational amplifier (OPAMP) [35-36]. To implement the design, we have to select some voltage level for QSD. In present study, we have selected the following voltage level for QSD: $\bar{3} \approx -3$ volts, $\bar{2} \approx -2$ volts, $\bar{1} \approx -1$ volts, $0 \approx 0$ volts, $1 \approx 1$ volts, $2 \approx 2$ volts and $3 \approx 3$ volts respectively. For design & implementation purpose, we have made some modification in the common circuit of digital to analog converter using OP-

Hence, the output voltage of the A/D converter circuit (V2 point) is [29],

Inputs (Volt)			Outputs [V_0] (Volts)				
C	B	A	Ideal	Calculated	Experimental	Error ₁	Error ₂
5	0	5	-3	-2.79	-2.86	0.07	-0.14
5	5	0	-2	-1.77	-1.67	0.10	-0.33
5	5	5	-1	-0.74	-0.45	0.29	-0.26
0	0	0	0	0.28	-0.09	0.37	0.09
0	0	5	1	1.31	1.31	0.00	0.31
0	5	0	2	2.33	2.40	0.07	0.40
0	5	5	3	3.57	3.53	0.04	0.53

Figure 2(b): Block Diagram of the Single Digit QSD Converter Block (bQ -block)

AMP to get 'Single-digit QSD converter'. The electronic circuit for Single-digit QSD converter is shown in the fig-2(a) and the corresponding logic table with analog values were given in Table 1. In this design, we have used two operational amplifiers (OPAMP). For experimental setup, we have used the IC 741 (OPAMP) and IC 74LS04 (NOT GATE). OPAMP1 acts as 3-bit digital-to-analog (D/A) converter and OAMP2 acts as inverting gate. The inputs C, B, A are the binary (2's complement) with logical state 1 (dc voltage range of 3.5 to 5 volt) or 0 (dc voltage range 0 to 1 volt) where input C is the most significant bit (MSB) and A is the least significant bit (LSB). C is connected to the input of the OPAMP1 through binary NOT gate. When C=0 volt then voltage at V1 point is 5 volt (experimental measured value is 4.42 volt) and when C=5 volt then voltage at V1 point is 0 volt (experimental measured value is 0.11 volt) i.e. we can say that inputs of the D/A converter are $\bar{C}$, B, A. If the inputs (C, B, A) are of logical state 000 then, actually 100 (equivalent to 4 in decimal) is fed to the input of the D/A converter unit. To get logic output '0', we need to put an offset from -12 volt through resistance R_{off} according to the fig-2(a). The block diagram of this binary to QSD converter (bQ -block) circuit is shown in the fig-2(b).

The offset voltage produces in the circuit is

$$-\frac{R_f}{R_{off}}(-12) = 4 \quad (4)$$

$$-5 \cdot \left(\frac{R_f}{R} LS_C + \frac{R_f}{2R} LS_B + \frac{R_f}{4R} LS_A \right) + \frac{12 \cdot R_f}{R_{off}} \quad (5)$$

Figure 3: Experimental, Theoretical and Ideal QSD values for Different Binary Inputs

where LS_C , LS_B and LS_A are the logical states of the input C, B and A respectively. Using $R_f = 820K\Omega$, $R = 1M\Omega$ and calculating from the equation (4) $R_{off} = 2.4M\Omega$ (in experiment we use $R_{off} = (2.2M\Omega + 330K\Omega + 47K\Omega) = 2.577M\Omega$). In the experimental setup we find the voltage for binary 'logical-1' state is 5.08 volt. Hence putting these values of resistance and experimentally measured voltage, we found the following results as shown in Table 1. Fig. 3 shows the experimental, theoretical and ideal QSD values for different binary inputs. The graphical representation of the output voltage with time is also shown in the Fig 4. From table-1 we see that there are two types of errors, one is difference between experimental results and theoretical value (we define it $Error_1$) and other is difference between experimental and ideal one (we defined it as $Error_2$).

$$Error_1 = |Experimental - theoretical| \quad (6)$$

$$Error_2 = (Ideal - Experimental) \quad (7)$$

Figure 4: Output waveform of Binary to QSD Converter Circuit. Solid Line: Calculated Result, Dotted Line: Experimental Result

Figure 5(a): $Error_1$ Detected in Experiment and Theory for Different set of Binary Inputs

These errors are plotted for different logical binary inputs in Fig. 5(a) and 5(b) respectively. Here we see that errors become small for positive QSD numbers than negative QSD numbers.

Figure 5(b): $Error_2$ found in Experiment and Ideal QSD values for Different set of Binary Inputs

Binary to QSD conversion by electronic circuit is not so easy, because in ordinary quaternary conversion required only 4 states, but in QSD conversion we required three extra logical states. To represent these states, voltage level selection is important and the difference between two successive states should be distinguishable with precision. Otherwise, data error may occur. The sources of error are noises present in the components used to design the circuit. The noise also depends on frequency of operation. Noise minimization is an important factor in this regards. OPAMP operates in high voltage span -12V to +12V, but the power dissipation is high enough in respect to CMOS based MVL circuits [37-38]. It may operate at the frequency 2.2 MHz. One the other hand our proposed circuit can be designed with ν MOS- OPAMP which has greatly enhanced the accuracy of analog computation. Namely, the output offset voltage appearing in a multi-valued logic gate does not increase with the increase in the number of input terminals and the output offset does not propagate to the next stage, thus making it very promising for implementing multi-valued logic integrated circuits [39].

IV. CONCLUSION AND DISCUSSION

In this paper, we have reported a new and easy method for conversion from binary number (2's compliment representation) to quaternary-signed digit (QSD). Some important issues as follows are discussed. The above techniques can be easily used for designing n -bit binary $(a_n a_{n-1} \dots a_2 a_1 a_0)_2$ to q -digit QSD data $(m_q m_{q-1} \dots m_2 m_1 m_0)_4$ with the help of single bit QSD converter unit (bQ -block). The corresponding circuit is shown in the fig-6. Here binary bits a_n , a_{n-1} and a_{n-2} are connected with three inputs 'C', 'B' and 'A' respectively of bQ_n -block. The output of this circuit is m_q . Again, a_{n-3} and a_{n-4} binary bits are connected into 'B' and 'A' inputs of next bQ_{n-1} -block. 'C' input of this block is grounded i.e. fed to 0 volt. The output of this block is m_{q-1} . Other bits are put into other bQ -blocks (bQ_{n-1} , ..., bQ_1 , bQ_0 respectively) as the same way of bQ_{n-1} -block. MSB of this converted QSD number is only signed bit. So, if we look only

Figure 6: n -bit Binary Data to q -digit QSD Data Conversion Circuit

the MSB then, we can easily understand (without calculation) whether it is positive or negative. If the MSB of any QSD-data is one of $\bar{3}$, $\bar{2}$, $\bar{1}$ then, the data is negative. Otherwise it is positive.

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