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An Efficient Reverse Converter Design for Five Moduli Set RNS

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Abstract: For designing high speed digital systems, it considered so many factors, among those the Number System, what it uses plays a crucial role. The Residue number system provides the inherent properties such as Carry-free operations, Parallelism and Fault Tolerance. While designing RNS, the selection of choice of moduli set plays a key role. The 3n-bit dynamic range RNS moduli set $\{2^{n-1}, 2^n, 2^{n+1}\}$ is the most famous RNS moduli set because of its simple and well formed balanced moduli. However, the arithmetic operations with respect to the modulus 2^{n+1} are complex and dynamic range is not sufficient for applications that require larger dynamic range. The 4n-bit dynamic range four moduli set minimize the dynamic range, asymmetric moduli channel length and long conversion delay. In this paper review on, a special five moduli set (2^n-1, 2^n, 2^n+1, 2^{n+1}-1, 2^{n-1}-1) for even n . It exploits the special properties of the numbers of the form $2^n \pm 1$, and extends the dynamic range of present triple moduli $\{2^{n-1}, 2^n, 2^{n+}1\}$ based systems. It has dynamic range that can represent up to 5n-1 bits while keeping the moduli small enough and converter efficient. In this review paper reverse converter design is done with the Chinese Remainder Theorem (CRT) and the results are compared with the Mixed Radix Conversion theorem and also with three and four moduli sets.

Keywords: Residue Number System (RNS), Chinese Remainder Theorem (CRT), Dynamic Range (DR), Mixed Radix Conversion.

1. INTRODUCTION

The Residue Number System is a very old number system. It was founded by Sun Tzu. The basic idea of the RNS is based on uniquely representing large binary numbers using a set of smaller residues, which results in carry-free, high-speed and parallel arithmetic operations [1] [2]. This system is based on modulus operation, where the divider is called modulo and the remainder of the division operation is called residue. This fact encourages the implementation of RNS in some applications where intensive processing is inevitable.

The main characteristic that distinguishes the RNS from other number systems is that the standard arithmetic operations; addition, subtraction and multiplication are easily implemented, whereas operations such as division, root, comparison, scaling and overflow and sign detection are much more difficult. Therefore, the RNS is very useful in applications that require a large number of addition and multiplication, and a minimum number of comparisons, divisions and scaling. In other words, the RNS is preferable in applications in which additions and multiplications are critical. Such applications are cryptography, Digital Signal Processing, image processing, speech processing and transforms [1]-[3].
The RNS is an unconventional number system i.e., defined in terms of relatively Prime Moduli Set $\{m_1, m_2, \ldots, m_n\}$ that GCD $(m_i, m_j) = 1$ for $i \neq j$. The residue set is given as $\{x_1, x_2, \ldots, x_n\}$ is a set of smaller integers used to represent integer X. When the integer X is divided by modulus m_i, the least positive remainder is obtained is called the residue x_i. It can be given as:

$$X \bmod m_i = x_i$$

An alternative notation is given as

$$|X|_{m_i} = x_i$$

The Dynamic Range is the multiplication of the modulus of the moduli set $\{m_1, m_2, \ldots, m_n\}$ and is denoted by M. Mathematical it is given as

$$M = m_1 * m_2 * \ldots * m_n \text{ or } M = \pi^n_{i=1} m_i$$

The RNS based system contains three major blocks, such as Forward Converter, RNS Processor and Reverse Converter. The Forward converter is used to convert weighted –binary number to Residue number. This process is simple and fast. RNS processer performs the required operations such as addition, subtraction and multiplication on the given residue numbers and it gives it to the reverse converter, it is also simple and fast. Reverse converter is used to convert Residue number to weighted-binary conversion [3]. The Reverse conversion process is more

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difficult and introduces more overhead in terms of speed and complexity. For reverse conversion two algorithms are available namely Chinese remainder theorem (CRT) and mixed radix conversion (MRC). The CRT is desirable because the data conversion can be parallelized, while MRC is sequential process by its nature, it has less complex circuitry and slow modulo-M-operation, for different radixes. Whereas CRT requires large modulus adders operation in parallel manner.

1.1 Chinese Remainder Theorem (CRT):

Consider the moduli set S= $\{m_1,m_2,m_3,..,m_n\}$ and let the RNS representation of an integer X be$\{x_1,x_2,x_3,......x_n\}$.Then the Chinese Remainder Theorem reconstructs X from its residues as follows

$$X= (X_1M_1Y_1+X_2M_2Y_2+..+X_nM_nY_n) \bmod M$$

Alternately, we can have

$$X= (\sum X_iM_iY_i) \bmod M \quad \text{where } i=1 \text{ to } n$$

Where,

$M= (m_1*m_2*m_3*......m_n)$

$M_i= M/m_i$ and $Y_i= (M_i^{-1}) \bmod m_i$

1.2 Mixed Radix Conversion (MRC):

Given an RNS number X be $\{x_1,x_2,x_3,.....x_k\}$ for the moduli set $\{m_1,m_2,m_3,......m_k\}$,the decimal equivalent of it can be computed as

$$X=a_1+a_2m_1+a_3m_1m_2+............+a_km_1m_2m_3....m_{k-1}$$

Where the Mixed Radix Digits (MRD) can be computed as:

$a_1 =x_1$

$a_2 =|(x_2-a_1)|m_1^{-1}|m_2|m_2$

$a_3 =|((x_3-a_1)m_1^{-1}|m_3-a_2)|m_2^{-1}|m_3|m_3$

:

:

$a_k =|(((x_k-a_1)|\, m_1^{-1}\,|\, m_k-a_2)|\, m_2^{-1}|\, m_k -....-a_{k-1})|m_{k-1}^{-1}|\, m_k\,|\, m_k$

For the MRDs a_i, $0\le a_i < m_i$, any positive number in the interval $\{0,\pi_{i-1}^{k}\, m_{i-1}\}$ can be uniquely represented.

2. SELECTION OF MODULI SET

In RNS, the most important issues that must be taking into account are, a proper moduli set selection, forward conversion, residue arithmetic units (RAU), and reverse conversion. Majority of the high performance reverse converter architectures available are based on the three moduli set $\{2^{n-1},2^n, 2^{n+1}\}$ [3]-[6]. However, this popular set is inefficient if increased parallelism is required to benefit from the residue arithmetic. It is inefficient in dealing with a large dynamic range. One way to overcome this inadequacy is to add extra moduli to this set from the same family ($2^n \pm1$). But it can be shown that if we add one or two more modulus to the triple moduli set, then the closed form multiplicative inverses become complex and cannot be implemented with simple hardware as in the case of triple moduli set. Four moduli superset $\{2^{n-1},2^n, 2^{n+1}, 2^{n+1}+1\}$ is proposed, but here two of the moduli are in the form of 2^n+1, which cause increase in dynamic range [7]. They also proposed a new supplementary four moduli superset $\{2^{n-1},2^n, 2^{n+1}, 2^{n+1}-1\}$ with efficient conversion in its residue- to –binary converter which minimizes the dynamic ranges [8]. Another class of conjugate moduli set is proposed [6]. But the moduli in these works are not pair wise relatively prime, hence it minimizes dynamic range, and it has asymmetric moduli channel length and long conversion delay. A five moduli set $\{2^{n-1},2^n, 2^{n+1}, 2^n+2^{n+1/2}+1, 2^n-2^{n+1/2}+1\}$ is proposed [9]. But here the new two moduli are not in the form of 2^n or $2^n \pm1$. This makes it hard to design efficient VLSI architectures. Another new five moduli set is $\{2^{n+1},2^n-1, 2^n+1, 2^{n+1}-1, 2^{n+1}+1\}$,where all the moduli are in the form of 2^n or $2^n \pm1$. Therefore, it has more efficient RAU. But the disadvantage is that the moduli set is not co-prime for any value of n, which reduces the dynamic range and also makes the residue–to-binary conversion algorithm complex. In this paper, we propose a new five moduli superset (2^n-1, 2^n, 2^n+1, 2^{n+1}-1, 2^{n-1}-1) for even values of n. The forward and reverse converter and the modular operations for this moduli set is more efficient, as the moduli are in the form of 2^n or $2^n \pm1$. There is only one modulus in the form of 2^n+1.

3. REVERSE CONVERTER DESIGN FOR FIVE MODULI SET USING MRC

In the existing method the reverse converter was designed for three, four and five moduli set using mixed radix conversion theorem. The MRC is a sequential process so it has high conversion delay and slow modulo additions.

3.1: THEORETICAL CALCULATIONS:
3.1.1: 3 MODULI SET

Moduli set m= $\{m_1, m_2, m_3\}$ = {3, 4, 5} and Residue set x=$\{x_1, x_2, x_3\}$ = {2, 3, 1}

The MRC can be given as $X=y_1+y_2m_1+y_3m_2m_1 \quad \rightarrow (1)$

Where $y_1 =x_1=2$

$y_2 = |\, |m_1|^{-1}_{m2}\, (x_2-y_1)|_{m2}$

$|m_1|^{-1}_{m2} = |\,3|^{-1}_{4}$

$3*k_1 = (1 \bmod 4)$

$k_1=3$

$y_2 = |3*(3-2)|4 =|3|4 =3$

$y_3 = |\,(m_2m_1)^{-1}_{m3}\,(x_3-(y_2m_1+y_1))\,|_{m3}$

$(m_2m_1)^{-1}_{m3} = (4*3)^{-1}_{5} = |12|^{-1}_{5}$

$12*k_2 = (1 \bmod 5)$

$k_2=3$

$y_3 =|3\;\{1-(3*3+2)\}\,|_5 = |-30|_5 = 0$

Substitute all values in equation (1)

$X = y_1+y_2m_1+y_3m_2m_1$

X=2+3*3+0*12

X=11

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3.1.2: 4 MODULI SET

Moduli set m= $\{m_1, m_2, m_3, m_4\} = \{5, 7, 8, 9\}$ and Residue set $x=\{x_1, x_2, x_3, x_4\} = \{1, 2, 3, 4\}$

The MRC can be given as $X=y_1+y_2m_1+y_3m_2m_1+y_4m_3m_2m_1 \rightarrow (1)$

Where $y_1 = x_1 = 1$

$y_2 = | |m_1|^{-1}_{m2} (x_2-y_1)|_{m2}$

$|m_1|^{-1}_{m2} = | 5|^{-1}_{7}$

$5*K_1 = (1 \bmod 7)$

$K_1=3$

$y_2 = |3*(2-1)|_7 = | 3 |_7 = 3$

$y_3 = | (m_2m_1)^{-1}_{m3} (x_3-(y_2m_1+y_1)) |_{m3}$

$(m_2m_1)^{-1}_{m3} = (7*5)^{-1}_{8} = |35|^{-1}_{8}$

$35*K_2 = (1 \bmod 8)$

$3*K_2 = (1 \bmod 8)$

$K_2=3$

$y_3 = |3 \{3-(3*5+1)\}|_8 = |-39|_8 = 1$

$y_4=|(m_3m_2m_1)^{-1}_{m4}(x_4-(y_3m_2m_1+y_2m_1+y_1))|_{m4}$

$(m_3m_2m_1)^{-1}_{m4} = (8*7*5)^{-1}_{9} = |280|^{-1}_{9}$

$280*K_3 = (1 \bmod 9)$

$1*K_3 = (1 \bmod 9)$

$K_3=1$

$y_4 = |1* \{4-(1*7*5+3*5+1)\}|_9 = |-47|_9 = 7$

Substitute all values in equation (1)

$X = y_1+y_2m_1+y_3m_2m_1+y_4m_3m_2m_1$

$X=1+3*5+1*7*5+7*8*7*5$

$X=2011$

3.1.3: 5 MODULI SET

Moduli set m= $\{m_1, m_2, m_3, m_4, m_5\} = \{15, 16, 17, 31, 7\}$

Residue set $x=\{x_1, x_2, x_3, x_4, x_5\} = \{7, 13, 4, 2, 3\}$

The MRC can be given as

$X=y_1+y_2m_1+y_3m_2m_1+y_4m_3m_2m_1+y_5m_4m_3m_1$

Where $y_1 = x_1 = 7$

$y_2 = | |m_1|^{-1}_{m2} (x_2-y_1)|_{m2}$

$|m_1|^{-1}_{m2} = | 15|^{-1}_{16}$

$15*K_1 = (1 \bmod 16)$

$K_1=15$

$y_2 = |15*(13-7)|_{16} = | 90 |_{16} = 10$

$y_3 = | (m_2m_1)^{-1}_{m3} (x_3-(y_2m_1+y_1)) |_{m3}$

$(m_2m_1)^{-1}_{m3} = (16*15)^{-1}_{17} = | 240 |^{-1}_{17}$

$240*K_2 = (1 \bmod 17)$

$2*K_2 = (1 \bmod 17)$

$K_2=9$

$y_3 = |9* \{4-(10*15+7)\}|_{17} = |-1377|_{17} = 0$

$y_4 = |(m_3m_2m_1)^{-1}_{m4} (x_4-(y_3m_2m_1+y_2m_1+y_1))|_{m4}$

$(m_3m_2m_1)^{-1}_{m4} = (17*16*15)^{-1}_{31} = |4080|^{-1}_{31}$

$4080*K_3 = (1 \bmod 31)$

$19*K_3 = (1 \bmod 31)$

$K_3=18$

$y_4 = |18* \{2-(0+150+7)\}|_{31} = |-2790|_{31} = 0$

$y_5=|(m_4m_3m_2m_1)^{-1}_{m5}(x_5-(y_4m_3m_2m_1+y_3m_2m_1+y_2m_1+y_1))|_{m5}$

$(m_4m_3m_2m_1)^{-1}_{m5} = (31*17*16*15)^{-1}_{7}$

$=|126480|^{-1}_{7}$

$126480*k_4 = (1 \bmod 7)$

$4*k_4 = (1 \bmod 7)$

$K_4=2$

$Y_5 = |2* \{3-(0+0+150+7)\}|_9 = |-308|_7 = 0$

Substitute all values in equation (1) $X=y_1+y_2m_1+y_3m_2m_1+y_4m_3m_2m_1+y_5m_4m_3m_2m_1$

$X=7+10*15+0+0+0$

$X=157$

4. REVERSE CONVERTER DESIGN FOR FIVE MODULI SET WITH PROPOSED CRT

In the proposed method the Chinese remainder theorem is used to design the reverse converter for the three, four and five moduli set. The CRT has low conversion delay and efficient architecture because of its parallel nature.

4.1 THEORETICAL CALCULATIONS:

4.1.1: 3 MODULI SET

Moduli set m= $\{m_1, m_2, m_3\} = \{3, 4, 5\}$ and Residue set $x=\{x_1, x_2, x_3\} = \{2, 3, 1\}$

The Chinese remainder theorem is given as

$X= | X_1M_1Y_1+X_2M_2Y_2+X_3M_3Y_3| \bmod M \rightarrow (1)$

Where $M=m_1*m_2*m_3$

$M= 3*4*5 = 60$

Where $M_i= M/m_i$

$M_1= M/m_1 = 60/3 = 20$

$M_2= M/m_2 = 60/4 = 15$

$M_3= M/m_3 = 60/5 = 12$

Where $Y_i=| M_i|^{-1}_{mi}$

$Y_1=|M_1|^{-1}_{m1} =| 20|^{-1} 3$

$20 Y_1= (1 \bmod 3)$

$2 Y_1= (1 \bmod 3)$

$Y_1 = 2$

Similarly $Y_2= |M_2|^{-1}_{m2} = |15|^{-1}_{4} = 3$

$Y_3= |M_3|^{-1}_{m3} = |12|^{-1}_{5} = 3$

Substitute all values in equation (1)

$X= | X_1M_1Y_1+X_2M_2Y_2+X_3M_3Y_3| \bmod M$

$X= |2*20*2+3*15*3+1*12*3| \bmod 60$

$X= |251| \bmod 60$

$X= 11$

4.1.2: 4 MODULI SET

Moduli set m= $\{m_1, m_2, m_3, m_3, m_4\} = \{5, 7, 8, 9\}$ and Residue set $x=\{x_1, x_2, x_3, x_4\} = \{1, 2, 3, 4\}$

The Chinese remainder theorem is given as

$X=| X_1M_1Y_1+X_2M_2Y_2+X_3M_3Y_3+ X_4M_4Y_4 | \bmod M \rightarrow (1)$

Where $M=m_1*m_2*m_3*m_4$

$M= 5*7*8*9 = 2520$

Where $M_i= M/m_i$

$M_1= M/m_1 = 2520/5 = 504$

$M_2= M/m_2 = 2520/7 = 360$

$M_3= M/m_3 = 2520/8 = 315$

$M_4= M/m_4 = 2520/9 = 280$

Where $Y_i=| M_i|^{-1}_{mi}$

$Y_1=|M_1|^{-1}_{m1} =| 504|^{-1}_{5}$

$504 Y_1= (1 \bmod 5)$

$4 Y_1= (1 \bmod 5)$

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$Y_1 = 4$

Similarly $Y_2 = |M_2|^{-1}{}_{m2} = |360|^{-1}{}_7 = 5$

$Y_3 = |M_3|^{-1}{}_{m3} = |315|^{-1}{}_8 = 3$

$Y_4 = |M_4|^{-1}{}_{m4} = |280|^{-1}{}_9 = 1$

Substitute all values in equation (1)

$X = |\ X_1M_1Y_1 + X_2M_2Y_2 + X_3M_3Y_3 + X_4M_4Y_4\ |$ mod M

X=|1*504*4+2*360*5+3*315*3+4*280*1| mod 2520

X= |9571| mod 2520

X= 2011

4.1.3: 5 MODULI SET

Moduli set m= $\{m_1, m_2, m_3, m_3, m_4, m_5\} = \{15, 16, 17, 31, 7\}$ Residue set $x = \{x_1, x_2, x_3, x_4, x_5\} = \{7, 13, 4, 2, 3\}$
Chinese remainder theorem is given as

$X = |\ X_1M_1Y_1 + X_2M_2Y_2 + X_3M_3Y_3 + X_4M_4Y_4 + X_5M_5Y_5|$ mod M $\rightarrow$ (1)

Where $M = m_1 * m_2 * m_3 * m_4 * m_5$

M= 15*16*17*31*7 = 885360

Where $M_i = M/m_i$

$M_1 = M/m_1 = 885360/15 = 59024$

$M_2 = M/m_2 = 885360/16 = 55335$

$M_3 = M/m_3 = 885360/17 = 52080$

$M_4 = M/m_4 = 885360/31 = 28560$

$M_5 = M/m_5 = 885360/7 = 126480$

Where $Y_i = |\ M_i|^{-1}\ m_i$

$Y_1 = |M_1|^{-1}\ m_1 = |\ 59024|^{-1}\ 15$

$59024\ Y_1 = (1 \bmod 15)$

$14\ Y_1 = (1 \bmod 15)$

$Y_1 = 14$

Similarly $Y_2 = |M_2|^{-1}\ m_2 = |55335|^{-1}\ 16 = 7$

$Y_3 = |M_3|^{-1}\ m_3 = |52080|^{-1}\ 17 = 2$

$Y_4 = |M_4|^{-1}\ m_4 = |28560|^{-1}\ 31 = 7$

$Y_5 = |M_5|^{-1}\ m_5 = |126480|^{-1}\ 7 = 2$

Substitute all values in equation (1)

$X = |X_1M_1Y_1 + X_2M_2Y_2 + X_3M_3Y_3 + X_4M_4Y_4 + X_5M_5Y_5\ |$ mod M

X=|7*59024*14+13*55335*7+4*52080*2 +2*28560*7+3*126480*2| mod 885360

X= |12395197| mod 885360

X= 157

5. SIMULATION RESULTS

The proposed and existing reverse converter architectures are simulated and synthesized in Xilinx ISE Design Suite 14.7 version using Verilog HDL. The figure1 and 2, figure 3 and 4, and figure 5 and 6 shows the simulated waveforms of the reverse converter for three, four and five moduli set with MRC and CRT respectively. The table1 shows the performance analysis of the reverse converter design with different moduli sets.

The three moduli set is $(2^n-1, 2^n, 2^n+1)$. Here we take n=2, so the moduli set is {3, 4, 5} and residue set is {2, 3, 1}. The result is 11(1011).

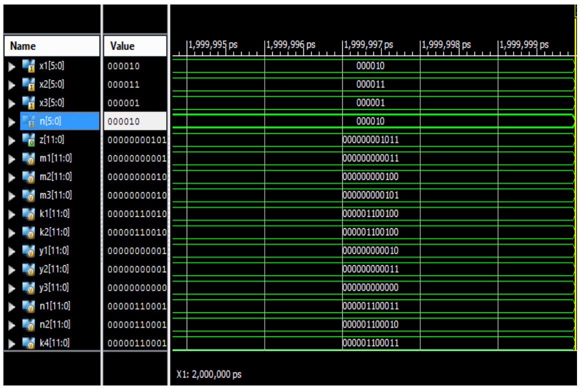

Fig.1: MRC simulation results for three moduli set

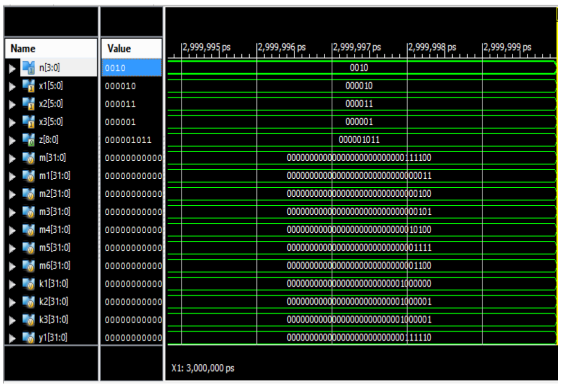

Fig.2: CRT simulation results for three moduli set.

The four moduli set is $(2^{n-1}+1, 2^n-1, 2^n, 2^n+1)$. Here we take n=3, so the moduli set is {5, 7, 8, 9} and residue set is {1, 2, 3, 4}. The result is 2011(11111011011).

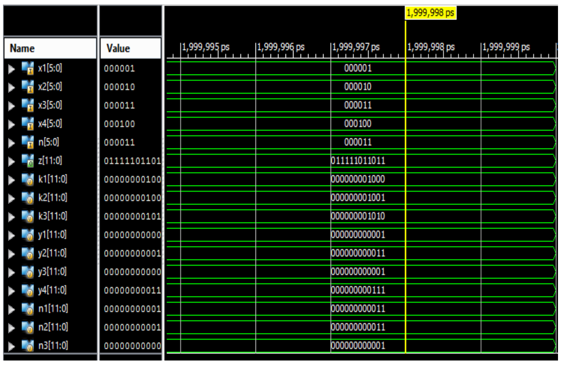

Fig.3: MRC simulation results for four moduli set

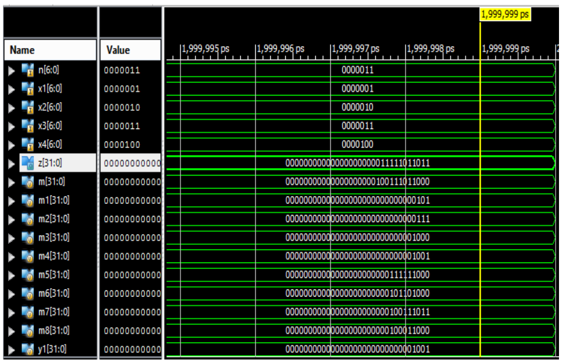

Fig.4: CRT simulation results for four moduli set.

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Here we take n=4.So the five moduli set is (2^n-1, 2^n, 2^n+1, 2^{n+1}-1, 2^{n-1}-1) = (15, 16, 17, 31, 7) and the residue set is (7, 13, 4, 2, 3) .The result is 157 (10011101)

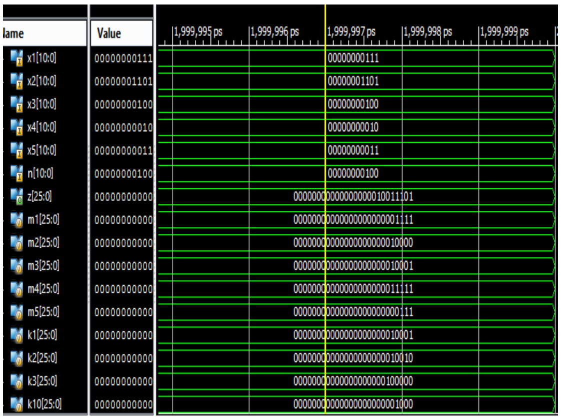

Fig.5: MRC simulation results for five moduli set

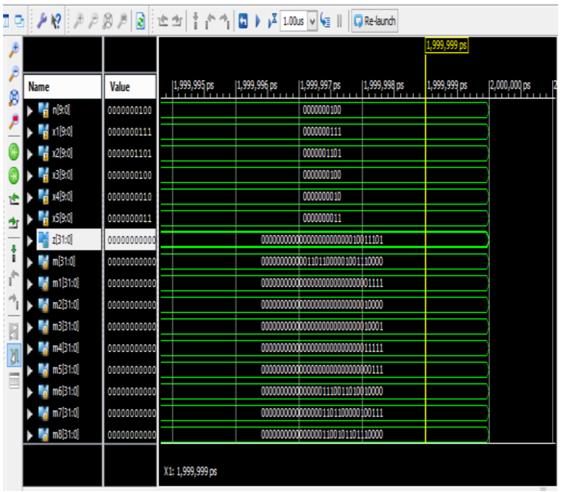

Fig.6: CRT simulation results for five moduli set

The proposed reverse converter design for five moduli set using CRT is efficient than the existing MRC reverse converter design.

Moduli set	Delay (ns)		Dynamic Range (bits)
	MRC	CRT	
5Moduli	638.60	186.71	5n-1
4Moduli	223.21	175.59	4n
3Moduli	185.65	171.12	3n

Table 1: Performance Analysis

6. CONCLUSION

This work aims to build an efficient Reverse converter for five moduli set residue number system, with high dynamic range to increases the parallelism.

The proposed method has less conversion delay (high speed) than the existing method. It has high dynamic range up to 5n-1.The performance analysis as shown in the table 1.

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