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Rain Fade Mitigation Technique Using Residue Number System Architecture on KU Band Satellite Communication Link

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Abstract: Rain fade is the loss of signal power at the receiver of a telecommunication system mainly due to absorption and scattering caused by rain in the transmission medium, especially at frequencies above 10 GHz. In order to combat the loss of the signal power at the receiver, there is the need to employ rain fade mitigation techniques. Consequently, researchers have been studying how rain affects the signal in different geographical locations as well as proposing some mitigation techniques. Power control is one of the mitigation techniques that have been proposed. But this technique has some associated challenges. Increasing the power will lead to an increase in cost of transmission which will eventually be passed on to the consumer thereby making satellite services expensive. It introduces a delay in compensation due to link estimation and coordination. Also, because of health concerns there is a limit to the amount of power that can be radiated to the ground and this is governed by international agreements. Another power management drawback in using this technique is that, it is essential to track the power continuously to ensure that the power values are not set too high, which can lead to the front end of the receiver being overdriven and eventually leading to a shutdown or physical damage. In this paper, we address the power control challenges, by leveraging on the inherent properties of Residue Number System (RNS) to propose an RNS architecture using the moduli set $\{2^{2n+1}-1, 2^{2n}-1, 2^{2n}\}$ that can mitigate rain fade in the satellite link. In digital communication systems, the bit energy, e_b, is the most important parameter in determining the communications link performance. Numerical analysis shows that the proposed scheme performs better than the traditional method as indicated in the high energy per bit value obtained in the proposed system in comparison with the traditional method.

Keywords: Rain Fade Mitigation, Power Control, Residue Number System

1. Introduction

The immense strength of satellite broadcasting lies in its ability to access a limitless number of sites without the need for any physical links irrespective of their location. A satellite receives the up-linked signal, lowers its frequency and rebroadcasts it to any geographical area desired. Ku band satellites are designed for spot beams, operating in the higher range of 12 GHz and allow smaller antennas to capture their signals [1]. The satellite signal transmission process is shown in Figure 1.

Rainfall is known to be the major cause of signal impairment in Ku band. In view of this, researchers have been developing rain rate and rain attenuation models to characterise and predict the effects of rain and propose mitigation techniques. However, very little has been done with regards to rain attenuation mitigation. A research was conducted on mitigation technique for rain fade using frequency diversity method by [2] in Malaysia. The frequency diversity method was used; however, this technique is not suitable because ground stations and satellites using this technique must be equipped to operate in dual frequency mode. The method is also complex because the receiver will have to pick up all the different signals. Power control is one of the mitigation techniques that have been proposed. In 2019, [3] conducted a research on rain attenuation mitigation on wireless communication link using adaptive power control. The model employed a feedback-based transmission power control algorithm to dynamically maintain individual link quality over time using Proportional Integral Derivative (PID). They concluded that PID has an enhanced response because it has shorter rising time and setting time when compared with proportional and proportional Integral controller systems. Their solution also focused on 5 GHz spectrum. But the use of power control is ineffective and expensive. This is because a satellite transmitter that offers coverage to a variety of users at different geographic location needs to work continuously at or near its peak power to overcome the overall attenuation encountered by only one of the ground stations. Again there are concerns regarding the safety of the amount of power that can be radiated to the ground and this is governed by international agreements [4]. Moreover, there are issues of intersystem interference with the increase in power level. This technique also requires some form of user intervention. Therefore it is imperative that other methods be considered to combat the effect of rain fade and restore acceptable performance on the communication link other than increasing the power. In this research, we leverage on the inherent properties of RNS in developing a cost effective solution to mitigate the effect of rain attenuation on the satellite communication link. This is achieved by using converters that changes the number system to RNS architecture before transmission. This is done using a forward converter at the transmitter. A reverse converter at the receiver then converts back from RNS to the traditional number representation. By this procedure, the energy per bit can be greatly enhanced so that even in the unlikely event of the signal encountering a rain event on the link, there will still be sufficient energy at the receiver to allow for the proper decoding of data.

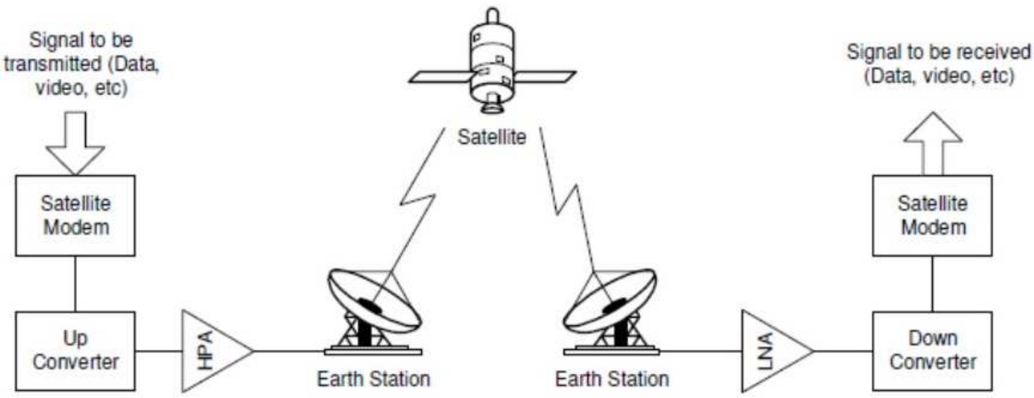

Figure 1. *The Satellite Transmission System.*

2. Residue Number System

Residue Number System (RNS) is a number system with numerous advantages. It is a well-established fact, that a number of digital devices naturally depend on number systems and to a large extend digital devices are built using binary number system. RNS has been used efficiently in communication systems [5], Digital Signal Processing for filtering, Convolutions and Correlations [6]. Residue Number System (RNS) is defined by the set S which includes N integers that are pair-wise relatively prime. That is S=$\{m_{1,} m_{2,} \dots m_N\}$, where gcd $(m_i, m_j) = 1$ for $i, j = 1, \dots N$ and $i, j \neq 1$ and gcd means the greatest common divisor [7]

Every integer X in $[0, M - 1]$ can be uniquely represented with an N-tuple where,

$$M = \prod_{i=1}^{n} m_i, X \rightarrow (R_1, R_2, \dots \dots \dots R_N) \text{ } and \text{ } R_i = |X|_{m_i} = (X \text{ } mod \text{ } m_i); for \text{ } i = 1 \text{ } to \text{ } N.$$

The set S and the number R_i are called the moduli set and the residue of X modulo m_i, respectively [8-10].

Over the past years there has been renewed interest especially in the area of arithmetic computation and signal processing applications such as Fast Fourier transforms, digital filtering and image processing [11-14]. The inherent carry free operations, parallelism, borrow-free subtraction, single step multiplication without partial product and fault-tolerance properties of Residue Number System have made it a choice of technology for high precision and high throughput rate Digital Signal Processing applications where only repeated multiplications and additions are required [15-17].

3. The Proposed Design

The complexity and varied problems associated with rain attenuation mitigation techniques makes it necessary to explore other methods. One way is the reduction in the data rate. But instead of reducing the size of data to be transmitted or transmitting one piece at a time, a better approach to use is by employing a different number system. The RNS is the most reliable solution, since this number system is able to reduce a given decimal to residues in respect to a given moduli set. And thus the residues to be transmitted will amount to fewer bits than the number of bits produced by the conventional number system. Therefore designing converters that can greatly reduce the number of bits before transmission will result in a higher energy-per-bit to noise density ratio which will lead to a higher carrier-to-noise ratio at the receiver leading to better performance of the communication link. Another advantage is that the system does not require human intervention during rain attenuation mitigation. The proposed system architecture is shown in Figure 2.

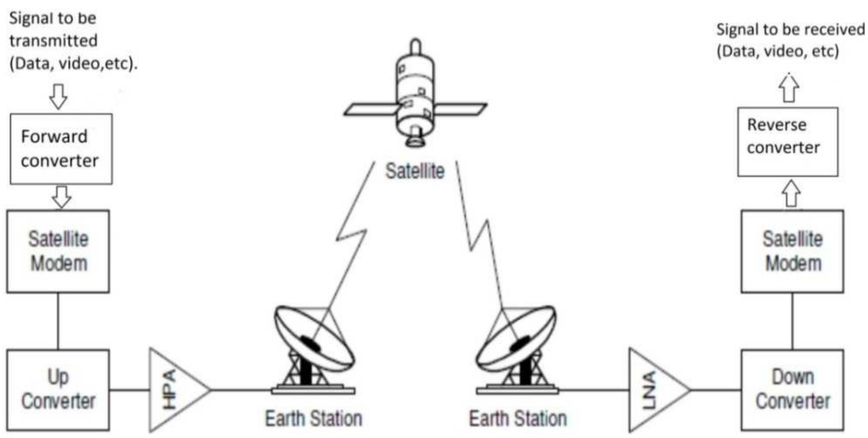

Figure 2. *Satellite communication link with RNS converters.*

A. Forward Conversion Process For Moduli Set $\{2^{2n+1}-1,\ 2^{2n}-1,\ 2^{2n}\}$

This moduli set was chosen because it gives a large dynamic range for small values of n. In satellite communication it is advisable to transmit large amount of data at a time because of the long delay. The moduli set of the proposed scheme works for both odd and even numbers of n > 1.

Given the moduli set, let

$$m_1 = 2^{2n+1}-1, m_2 = 2^{2n}-1 \text{ and } m_3 = 2^{2n};$$

An integer X in the range $[0, M)$ is a $(6n+1)$-bit number which binary representation is as follows:

$$X = X_{6n}X_{6n-} \dots X_1X_0 \tag{1}$$

This weighted representation has a unique equivalent RNS representation $x_i = |X|_{m_i} \Leftrightarrow (x_1, x_2, x_3)$; and in order to compute the x_i's, Equation (1) is partitioned into two $2n$-bit blocks and a $(2n+1)$-bit block as:

$$\left.\begin{aligned} \Lambda_1 &= \textstyle\sum_{j=0}^{2n-1} x_j 2^j \\ \Lambda_2 &= \textstyle\sum_{j=2n}^{4n-1} x_j 2^{j-2n} \\ \Lambda_3 &= \textstyle\sum_{j=4n}^{6n} x_j 2^{j-4n} \end{aligned}\right\} \tag{2}$$

this implies

$$X = \Lambda_1 + 2^{2n}\Lambda_2 + 2^{4n}\Lambda_3 \tag{3}$$

Such that,

$$\begin{aligned} x_1 &= |X|_{2^{2n+1}-1} \\ &= |\Lambda_1 + 2^{2n}\Lambda_2 + 2^{4n}\Lambda_3|_{2^{2n+1}-1} \\ &= ||\Lambda_1|_{2^{2n+1}-1} + |2^{2n}\Lambda_2|_{2^{2n+1}-1} + |2^{4n}\Lambda_3|_{2^{2n+1}-1}|_{2^{2n+1}-1} \\ &= |\Lambda_1 + 2^{2n}\Lambda_2 + 2^{2n-1}\Lambda_3|_{2^{2n+1}} \end{aligned} \tag{4}$$

$$\begin{aligned} x_2 &= |X|_{2^{2n}-1} = |\Lambda_1 + 2^{2n}\Lambda_2 + 2^{4n}\Lambda_3|_{2^{2n}-1} \\ &= ||\Lambda_1|_{2^{2n}-1} + |2^{2n}\Lambda_2|_{2^{2n}-1} + |2^{4n}\Lambda_3|_{2^{2n}-1}|_{2^{2n}-1} \\ &= |\Lambda_1 + \Lambda_2 + \Lambda_3|_{2^{2n}-1} \end{aligned} \tag{5}$$

and

$$x_3 = |X|_{2^{2n}} = \Lambda_1 \tag{6}$$

The block diagram for the forward conversion is represented in Figure 3; it employs simple adders made up of Carry Save Adders (CSAs) and Carry Propagate Adders (CPAs).

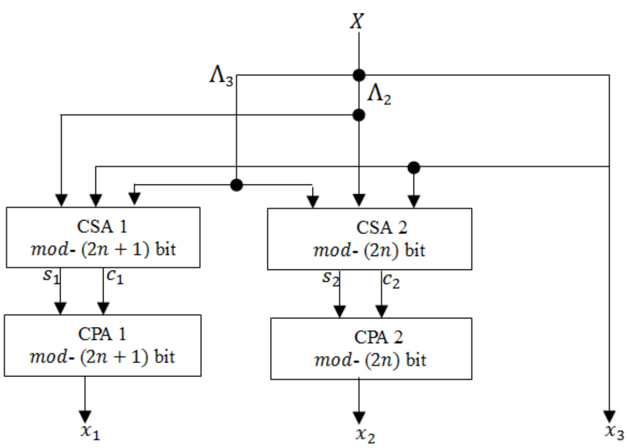

Figure 3. *Block Diagram for Forward Convertor.*

B. Bit Energy Computation

For digital communications, the bit energy, e_b , is more helpful for determining the link's performance than the carrier power. The link efficiency can be reduced in two ways: if the carrier power, c, is decreased, and/or if the noise power is increased. For example, the carrier power is reduced by the increase in the number of bits to be transmitted and the noise power is increased by the absorption and scattering of the signal by rain drops. Thus the larger the value of e_b, the better the performance of the link holding the noise power constant. By employing RNS architecture we will greatly reduce the number of bits to be transmitted thereby allowing more power to be available to fewer bits. In Equation (7), a relationship is established between the bit energy and the carrier power as

$$e_b = c\,T_b \tag{7}$$

where T_b is the bit duration in second (s) and c is the carrier power in watts. The energy-per-bit to noise density ratio, $\left(\frac{e_b}{n_o}\right)$, is the most widely used parameter to evaluate the performance of a digital communication link. And $\left(\frac{e_b}{n_o}\right)$ is related to $\left(\frac{c}{n_o}\right)$ by

$$\left(\frac{e_b}{n_o}\right) = T_b\left(\frac{c}{n_o}\right) = \frac{1}{R_b}\left(\frac{c}{n_o}\right) \tag{8}$$

Therefore by eliminating the noise component and power, it can be observed from Equation (8) that

$$e_b \propto \frac{1}{R_b} \tag{9}$$

Again, introducing the carrier power, c, as a constant, Equation (9) can be rewritten as

$$e_b = \frac{c}{R_b} \tag{10}$$

where e_b is the energy-per-bit, c is the power at the carrier and R_b is the bit rate, in bits per second (bps).

C. Reverse Conversion Process

The Mixed Radix Conversion (MRC) is employed to decode any number X in RNS representation to its binary/decimal equivalent. MRC was chosen because it suits the moduli set well especially with regards to computing the multiplicative inverses. It also avoids the use of big M which can result in complex computations. Also, the sequential nature of the MRC allows for a simplified architecture.

The general form of the MRC is given as follows;

$$X = d_1 + d_2m_1 + d_3m_1m_2 + \cdots + d_nm_1m_2m_3 \ldots m_{n-1} \tag{11}$$

Where $d_i, i = 1,2,\ldots,n$ are the Mixed Radix Digits (MRDs) and computed as follows:

$$d_1 = x_1,$$

$$d_2 = \left|(x_2 - d_1)|m_1^{-1}|_{m_2}\right|_{m_2},$$

$$d_3 = \left|\left((x_3 - d_1)|m_1^{-1}|_{m_3} - d_2\right)|m_2^{-1}|_{m_3}\right|_{m_3},$$

$$\vdots$$

$$d_n = \left|\left(\ldots\left((x_3 - d_1)|m_1^{-1}|_{m_n} - d_2\right)|m_2^{-1}|_{m_n} - \cdots - d_{n-1}\right)|m_{n-1}^{-1}|_{m_n}\right|_{m_n} \tag{12}$$

Therefore, X in the interval $[0, M)$ can be uniquely represented. And so we can re-write Equation (12) as

$$d_1 = x_1,$$

$$d_2 = |(x_2 - d_1)(1)|_{2^{2n}-1} = |x_2 - x_1|_{2^{2n}-1},$$

and

$$d_3 = \left|\left((x_3 - d_1)(-1) - d_2\right)(-1)\right|_{2^{2n}} = |(x_3 - x_1 + d_2|_{2^{2n}} \tag{13}$$

And Equation (11) then becomes

$$X = x_1 + d_2(2^{2n+1} - 1) + d_3(2^{2n+1} - 1)(2^{2n} - 1)$$

$$= x_1 + 2^{2n+1}d_2 - d_2 + 2^{4n+1}d_3 - 2^{2n}d_3 - 2^{2n+1}d_3 + d_3 \tag{14}$$

D. Hardware Realization

We now simplify Equations (13) and (14) as follows;

$$d_1 = x_{1,2n}x_{1,2n-1} \ldots \ldots \ldots x_{1,1}x_{1,0} \tag{15}$$

$$d_2 = \left|\underbrace{x_{2,2n-1}x_{2,2n-2}\,\dots\dots x_{2,1}x_{2,0}}_{2n-bits} - \left|\underbrace{x_{1,2n}x_{1,2n-1}\,\dots\dots\dots x_{1,1}x_{1,0}}_{2n+1-bits}\right|_{2^{2n}-1}\right|_{2^{2n}-1}$$

$$= \left|\underbrace{x_{2,2n-1}x_{2,2n-2}\,\dots\dots x_{2,1}x_{2,0}}_{2n-bits} + \underbrace{x_{11,2n-1}x_{11,2n-2}\,\dots\dots\dots x_{11,1}x_{11,0}}_{2n-bits}\right|_{2^{2n}-1}$$

$$= \underbrace{d_{2,2n-1}d_{2,2n-2}\,\dots\dots\dots\dots d_{2,1}d_{2,0}}_{2n-bits} \tag{16}$$

Where, $x_{11} = |-x_1|_{2^{2n}-1}$
and

$$d_3 = \left|\underbrace{x_{3,2n-1}\,\dots\dots x_{3,1}x_{3,0}}_{2n-bits}\,\underbrace{x_{11,2n-1}\,\dots x_{11,1}x_{11,0}}_{2n-bits} + \underbrace{d_{2,2n-1}\,\dots\dots d_{2,1}d_{2,0}}_{2n-bits}\right|_{2^{2n}}$$

$$= \underbrace{d_{3,2n-1}d_{3,2n-2}\,\dots\dots d_{3,1}d_{3,0}}_{2n-bits} \tag{17}$$

A simplification of Equation (14) for implementation is as follows:

$$X = L_1 + L_2 + L_3 + L_4$$

$$= \underbrace{\begin{matrix}\overbrace{0\dots0}^{2n}\underbrace{L_{1,4n}\dots L_{1,1}L_{1,0}}_{4n+1} + \overbrace{0\dots0}^{2n}\underbrace{L_{2,4n}\dots L_{2,1}L_{2,0}}_{4n+1} + \overbrace{0\dots0}^{2n+1}\underbrace{L_{3,4n-1}\dots L_{3,1}L_{3,0}}_{4n} \\ + \\ \underbrace{L_{4,6n}\dots L_{4,1}L_{4,0}}_{6n+1}\end{matrix}}_{6n+1} \tag{18}$$

where,

$$L_1 = A - d_2 + d_3$$

$$= \underbrace{A_{4n}A_{4n-1}\,\dots\dots A_1A_0}_{4n+1} + \overbrace{11\dots1}^{2n+1}\underbrace{\bar{d}_{2,2n-1}\dots\bar{d}_{2,1}\bar{d}_{2,0}}_{2n-bits} + \underbrace{d_{3,2n-1}\dots d_{3,1}d_{3,0}}_{2n-bits}\overbrace{00\dots0}^{2n+1} \tag{19}$$

and

$$A = x_1 + 2^{2n+1}d_2$$

$$= \underbrace{x_{1,2n}x_{1,2n-1}\dots x_{1,1}x_{1,0}}_{2n+1-bits}\overbrace{0\dots.00}^{2n-bits} \bowtie \underbrace{d_{2,2n-1}d_{2,2n-2}\dots d_{2,1}d_{2,0}}_{2n-bits}\overbrace{0\dots.00}^{2n+1-bits}$$

$$= \underbrace{x_{1,2n}x_{1,2n-1}\dots x_{1,1}x_{1,0}d_{2,2n-1}d_{2,2n-2}\dots d_{2,1}d_{2,0}}_{4n+1}$$

$$= A_{4n}A_{4n-1}\dots A_1A_0 \tag{20}$$

Whereas

$$L_2 = -2^{2n+1}d_3$$

$$= \underbrace{\underbrace{\bar{d}_{3,2n-1}\bar{d}_{3,2n-2}\dots\bar{d}_{3,1}\bar{d}_{3,0}}_{2n-bits}\overbrace{11\dots1}^{2n+1}}_{4n+1} \tag{21}$$

$$L_3 = -2^{2n}d_3$$

$$= \underbrace{\underbrace{\bar{d}_{3,2n-1}\bar{d}_{3,2n-2}\dots\bar{d}_{3,1}\bar{d}_{3,0}}_{2n-bits}\overbrace{11\dots1}^{2n}}_{4n} \tag{22}$$

$$L_4 = 2^{4n+1}d_3$$

$$= \underbrace{\underbrace{d_{3,2n-1}d_{3,2n-2}\dots d_{3,1}d_{3,0}}_{2n-bits}\overbrace{00\dots0}^{4n+1}}_{6n+1} \tag{23}$$

The schematic diagram for the reverse process is shown in

Figure 4. The anticipated implementation of the scheme is based on simple CSAs and CPAs. It begins with an operands preparation unit (OPU) which prepares and manipulates the routing of the bits of the respective residues once inputted. The second MRD, d_2 is computed using CPA1 which is $2n$-bits wide; the concatenation of bits does not require a hardware unit, but its results is relevant for further processing. CSA1 and CPA2 are used to compute for the third MRD, d_3 after which, the rest of the addition process is done in a cascading fashion thereby reducing the complexity which results in a simplified architecture. CPA 3 computes the save and carry from CSA 5 in order to get back the decimal or binary number, X. Regarding the hardware requirements of the unit; the total hardware (area) requirement is $(30n + 5)$ bits of full adders and a delay imposition of $(10n + 6)$ bits of full adders.

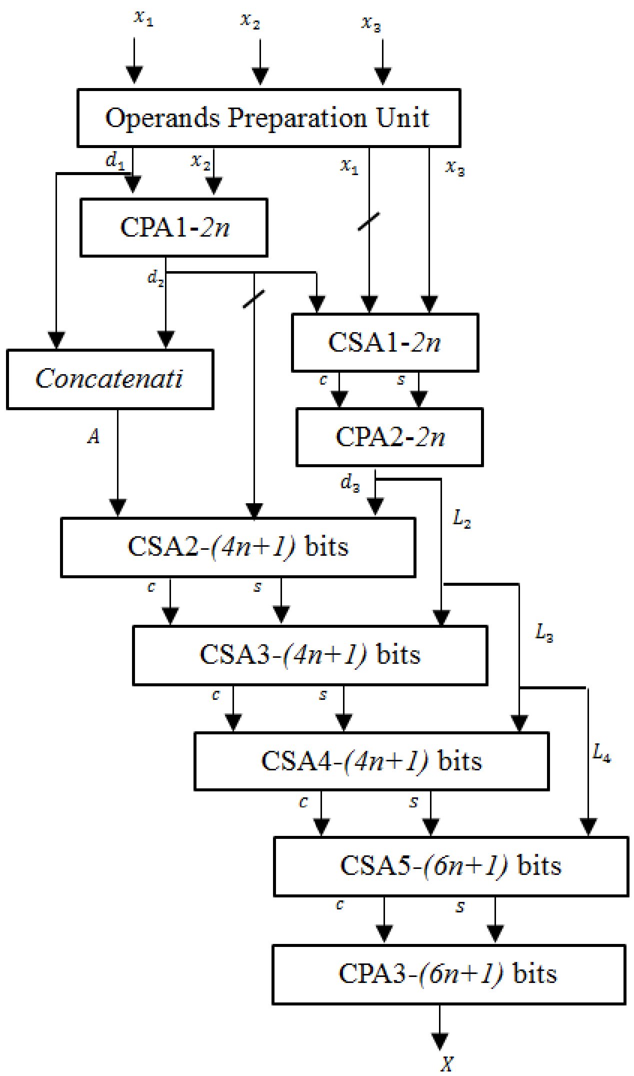

Figure 4. *Schematic Diagram for Reverse Conversion Process.*

4. Numerical Illustration

Given the moduli set $\{2^{2n+1} - 1,\ 2^{2n} - 1,\ 2^{2n}\}$, take $n = 2$. Consider X representing a character of a message to be transmitted, assume the ASCII value for that message $X =$ 6892. Then the conversion process is as follows; $6892 = 1101011101100$ (13-bits, since X is a $(6n + 1)$-bit number)

Thus, $\Lambda_1 = 1100, \Lambda_2 = 1110$ and $\Lambda_3 = 11010$

Therefore;

$$|6892|_{2^5-1} = |6892|_{31} = |12 + |16(14)|_{31} + |8(26)|_{31}|_{31}$$

$$= |12 + 7 + 22|_{31} = |41|_{31} = 10,$$

$$|6892|_{2^4-1} = |6892|_{15} = |12 + 14 + |26|_{15}|_{15}$$

$$= |12 + 14 + 11|_{15} = |37|_{15} = 7$$

And $|6892|_{2^4} = |6892|_{16} = 12$

And so $|6892|_{31|15|16} = (10,7,12)_{31|15|16}$

10 = 01010 7 = 0111 12 = 1100

And so $|6892|_{31|15|16} = (10,7,12)_{31|15|16}$

From the above illustration, it can be seen that the traditional method will convert the ASCII message, X = 6892, to binary which is $6892 = 1101011101100$ (13-bits, since X is a $(6n + 1)$-bit number). But this representation has a unique equivalent in RNS which is $|6892|_{31|15|16} = (10,7,12)_{31|15|16}$. Each of the moduli sets are channels that can be used to transmit the message X, but it is the binary equivalent of the residues that will be transmitted. The binary equivalent of $(10,7,12)_{31|15|16}$ is as follows:

10 = 01010 7 = 0111 12 = 1100

In order to perform the reverse conversion we find the MRD's a_1, a_2 and a_3 and compute the MRC in order to get back the value of X (i.e. message transmitted):

But $a_1 = x_1 = 10$

$$a_2 = |7 - 10|_{15} = 12$$

$$a_3 = \left|\left((12 - 10) \times 5 - 12\right) \times 15\right|_{16} = 14$$

Therefore,

$$X = 10 + 12(31) + 14(31)(15) = 6892$$

5. Performance Analysis

The performance of the communication link is determined by the energy per bit value. We can compare the worst case scenario of RNS architecture with the traditional method in terms of computing the bit energy. Let's assume a carrier power of 1W at the transmitter, with the traditional method, the transmit energy per bit, $e_b = \frac{1}{13} = 0.07692307692$ joules. In RNS representation, in the worst case scenario, $e_b = \frac{1}{5} = 0.2$ joules. It can be seen that excess energy of 0.1230769231 joules is available in RNS than in the traditional method. The RNS architecture therefore will perform better than the traditional method in the unlikely event of rainfall along the satellite communication path. In the second and third transmission channels, $e_b = \frac{1}{4} = 0.25$ joules. Table 1 shows the variation in the energy per bit between the proposed scheme using RNS and the traditional method. From Figure 5 it can be seen that for all values of n > 1, the proposed scheme will always outperform the traditional method. Therefore when there is rain fade along the satellite link, all other things being equal the proposed scheme will have enough energy available at the receiver to allow for proper data decoding at an acceptable bit error rate. It is also interesting to note that even the energy difference between the proposed scheme and the traditional scheme is higher than that of the traditional scheme. This can be seen in Figure 6.

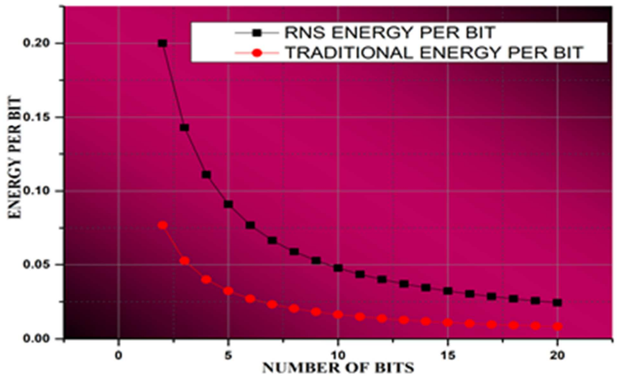

Figure 5. *Variation in Energy per Bit.*

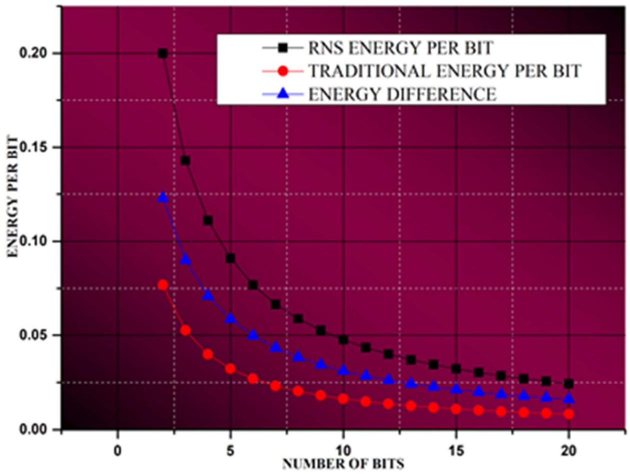

Figure 6. *Difference in Energy per Bit.*

Table 1. *Variation in Energy per Bit.*

N	Rns energy per bit	Traditional Energy Per Bit	Energy difference
2	0.2	0.076923077	0.123076923
3	0.142857143	0.052631579	0.090225564
4	0.111111111	0.04	0.071111111
5	0.090909091	0.032258065	0.058651026
6	0.076923077	0.027027027	0.04989605
7	0.066666667	0.023255814	0.043410853
8	0.058823529	0.020408163	0.038415366
9	0.052631579	0.018181818	0.034449761
10	0.047619048	0.016393443	0.031225605
11	0.043478261	0.014925373	0.028552888
12	0.04	0.01369863	0.02630137
13	0.037037037	0.012658228	0.024378809
14	0.034482759	0.011764706	0.022718053
15	0.032258065	0.010989011	0.021269054
16	0.03030303	0.010309278	0.019993752
17	0.028571429	0.009708738	0.018862691
18	0.027027027	0.009174312	0.017852715
19	0.025641026	0.008695652	0.016945373
20	0.024390244	0.008264463	0.016125781

6. Conclusion and Future Work

A novel rain attenuation mitigation technique has been proposed using RNS architecture on the satellite communication link. This solution does not require human intervention unlike other mitigation techniques. The technique involves the use of converters and a different number system from the traditional number system to reduce the number of bits to be transmitted. Forward converters to convert to RNS system before transmission and reverse converters to convert back to the traditional number system at the receiver. The moduli set chosen, $\{2^{2n+1} - 1,\ 2^{2n} - 1,\ 2^{2n}\}$, works for both odd and even numbers of n. Therefore, if the hardware realization of the proposed architecture is incorporated into the satellite communication system, it will help mitigate the attenuation due to rain since more energy will be made available to the individual bits. In future, the proposed scheme will be expanded to include a mechanism to detect and correct errors during transmission.

Conflict of Interest

The authors declare no conflict of interest in this research work.

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