ICI and PAPR Enhancement in MIMO-OFDM System Using RNS Coding

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Abstract —The Inter-Carrier-Interference (ICI) is considered a bottleneck in the utilization of Multiple-Input-Multiple-Output Orthogonal Frequency Division Multiplexing (MIMO-OFDM) systems, due to the sensitivity of the OFDM towards frequency offsets that losses the carrier orthogonality and generates signal interference that causes system performance degradation. In this paper Residue Numbers as a coding scheme is impeded in MIMO-OFDM systems, where the ICI levels is measured and evaluated with respect to the conventional ICI mitigation techniques as pulse shaping, windowing and self-cancellation techniques implemented in MIMO-OFDM system. The Carrier-to-Interference Ratio (CIR), the system Bit-Error-Rate (BER) and the Complementary Cumulative Distribution Function (CCDF) for MIMO-OFDM system with Residue Number System (RNS) coding are evaluated. The results demonstrated a performance enhancement of transmission model over the system without RNS implementation.

Index Terms— BER, CIR, ICI, Mitigation techniques, MIMO-OFDM system, RNS.

I. INTRODUCTION

In MIMO systems, the information data at both sides of the communication link is combined through the usage of various Space–Time Block Coding (STBC) algorithms to achieve either higher transmission data rates or enhance system BER performance for the same data rate [1], [2]. The OFDM as a multi-carrier modulation scheme had shown its ability to provide high transmission rates, because it has several unique features like robustness to multipath fading overcoming Inter-Symbol-Interference (ISI), efficient spectral usage, resilience towards impulse interference, overcoming time dispersion problems, flexibility and simplified equalization over wireless communication channels [3], [4].

For MIMO-OFDM communication systems [5], the orthogonality seen in OFDM technique is lost within the sub-carriers due to the sensitivity of OFDM to frequency offset induced from the Doppler shift between transmitter and receiver sides. This results in ICI between the transmitted symbols, which cause performance degradation [6].

Different ICI cancellation techniques are currently available like time-domain widowing, pulse shaping and frequency equalization, which reduce the ICI levels and thus improve the BER performance of MIMO-OFDM systems. These techniques are still costly and high complex either on the transmitter or receiver side. This paper propose an efficient ICI cancellation technique based on the utilization of Residue coding scheme; where the system is analyzed and compared to current mitigation techniques.

In section 2, the paper provides background on Residue Number system. Section 3 and 4 provide analysis of the ICI and a review for ICI cancellation schemes respectively. Section 5 describes the proposed MIMO-RNS-OFDM system. In section 6 the simulation results are provided to measure the system performance and finally in section 7, the conclusion has been supplied.

II. RESIDUE SYSTEM BACKGROUND

A. Residue Number System Review

The RNS represents large integers by set of smaller ones, and have two unique features; a carry-free arithmetic that enable to perform parallel mathematical operations related to the individual residue symbols, and no weight-information are carried between carriers which prevent error propagation [7].

RNS is defined by selecting v positive pair-wise relative primes m_i (i= 1, 2, 3 … v), such that any integer N, describing a message, is represented by the sequence (r_1, r_2 ..r_v) in the range $0<N<M_I$ in a unique matter, where:

$$r_i = N \pmod{m_i}; \text{ Residue of N upon division by } m_i \quad (1)$$

where:

r_i least positive remainder of N divided by modulus m_i

$$M_I = \prod m_i; \text{ is symbols' dynamic range.} \quad (2)$$

Then use Mixed Radix Conversion (MRC) method [8], to recover symbols. Where for the given set prime moduli and residue state of a number X, that number can be uniquely represented in mixed-radix form as seen in next:

$$X = \{z_1, z_2, \ldots, z_n\} \quad (3)$$

and;

$$X = z_1 + z_2m_1 + z_3m_2m_1 + \ldots + z_nm_{n-1}m_{n-2}\ldots m_1; \quad 0 \le z_i \le r_i \quad (4)$$

where; z_i is represented as function of the moduli and residue representations as seen in Table I;

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TABLE I: REPRESENTATION OF Z_i

Parameter	Representation
z_1	$= r_1$
z_2	$= \|\|m_1^{-1}\|_{m2}\ (r_2 - z_1)\|_{m2}$
z_3	$= \|\|(m_2 m_1)^{-1}\|_{m3}\ (r_3 - (z_2 m_1 + z_1))\|_{m3}$
Z_n	$= \|\|(m_n \ldots\ldots m_2 m_1)^{-1}\|_{mn}\ (r_n - (z_{n-1}\ m_{n-2} \ldots\ldots z_2 m_1 + z_1))\|_{mn}$

B. Redundant Residue Number System

The RNS moduli utilized for error detection and correction through implementation of additional RNS moduli as redundancy symbols, which is named "Redundant Residue Number System" (RRNS).

In this configuration, each redundant moduli selected to be greater than any of the other chosen moduli set and don't play any role in determining the system dynamic range. So, an RRNS is obtained by appending an additional $(u - v)$ number of moduli $m_{v+1}; m_{v+2}; \ldots;m_u$, where $m_{v+j} \geq \max\{m_1;m_2; \ldots\ldots;m_v\}$ is referred to as a redundant modulus to the previously introduced RNS. This is to form an RRNS of u positive, pairwise relative prime moduli. [9], [10]

For correction of the error, using MRC method, a test on each of the information moduli with the two redundant moduli is performed. Through the test it is able to identify and correct the bit which generated the error [11].

III. ANALYSIS OF INTER-CARRIER-INTERFERENCE

In MIMO-OFDM systems, the loss of orthogonally between subcarriers, increases the ICI between sub-carriers and leads to degradation for the system performance, which is caused by the Doppler shift generated from the relative motion between the transmitter and receiver sensitivity. This caused a frequency offset between sub-carriers, and results in a signal amplitude reduction and ICI, as presented in Fig. 1.

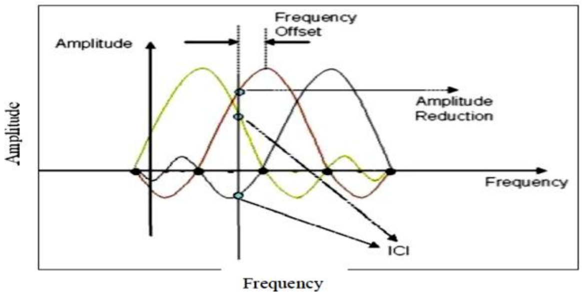

Fig. 1. Effect of carrier frequency offset

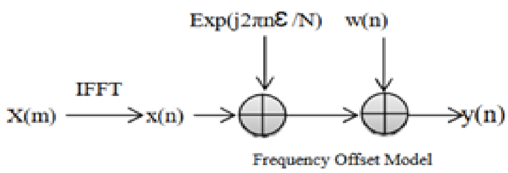

Fig. 2. Frequency offset model

The frequency offset (ε) is represented as seen in Fig. 2, where the received signal represented as;

$$Y(n) = x(n)e^{\frac{j2n\varepsilon}{N}} + W(n) \tag{5}$$

The effect of this frequency offset on the received symbol stream is shown in the received symbol Y(k) on the K^{th} sub-carrier.

$$Y(k) = X(k)\ S(0) + \sum_{l=0, l\neq k}^{N-1} X(l)S(l-k) + n_k \tag{6}$$

where:
X(k): Transmitted symbol for k^{th} sub-carrier,
n_k : FFT of w(n).
N: Total number of sub-carriers,
S(l-k): ICI components for received signal

The ICI components S(l-k), are the interfering signals on sub-carriers, where their complex coefficients are given by;

$$S(l\text{-}k) = \frac{\sin(\pi\ (l+\varepsilon-k)}{N \sin\left(\frac{\pi\ (l+\varepsilon-k)}{N}\right)} \exp(j\pi \left(1 - \frac{1}{N}\right) (l + \varepsilon - k) \tag{7}$$

IV. ICI MITIGATION TECHNIQUES

The accurate frequency and time synchronization are essential factors for OFDM technique. It is sensitive towards frequency offset factors as attenuation and rotation of subcarriers. For that reason the orthogonality is lost between subcarriers, yielding to constraint named Inter-Carrier Interference (ICI), which degrades the efficiency of the system performance.

A lot of researchers [12]–[14] proposed numerous ICI mitigation techniques to resolve this problem that are categorized as; frequency-domain equalization, time-windowing, self-cancellation, and Pulse shaping schemes. These techniques are employed also for decreasing the Peak-Average-Power Ratio (PAPR) through the reduction of side lobes in each carrier, permitting higher power to be transmitted to for a constant peak power, and making enhancement in the received SNR.

A detailed description of existing ICI mitigation techniques; are provided in the following subsections;

A. Self-Cancellation Technique

The input symbols are modulated to a group of subcarriers with pre-defined coefficients such that the ICI signals would cancel each other in the group. So, one data symbol is modulated into two consecutive sub-carriers, such that the data symbol 'a' is modulated in the first sub-carrier, and '-a' is modulated in to the second subcarrier. Consequently, the generated ICI between the two sub-carriers will be cancelled.

Through this scheme, it is possible to achieve an improvement in Carrier-Interference-Ratio (CIR) of about 20dB for $0<\varepsilon<0.5$ compared to the standard OFDM system, by decreasing the ICI levels [15]. Furthermore, this technique doesn't need an estimation feedback and is simple in implementation, but on the other hand, due to the redundancy introduced, more bandwidth is required.

B. Frequency Domain Equalization

A frequency pilot symbol is inserted between two sub-blocks, where it is able to determine the coefficients of

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the equalizers that are used in the frequency domain. [16], (Fig. 3).

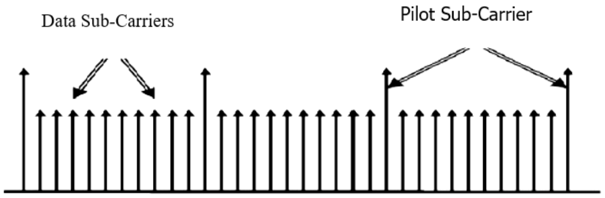

Fig. 3. Pilot Sub-carrier arrangement

The technique is similar to Maximum Likelihood (ML) estimation and Extended Kalman Filter (EKF), which estimates the offset and corrects it at the receiver end.

C. *Windowing Technique*

It is a system equalization in time-domain [17], where an exponential function is multiplied to the transmitted signal before calculating its Fourier transform seen in equation (8), with the purpose to reduce the effect of discontinuities at both ends of the discrete signal.

$$b_k = a_k\,(1 - \exp(j2\pi n/N)) \tag{8}$$

where; b_k transmitted data samples on the k^{th} subcarrier

This technique reduces the start and ends of waveform, reducing the transients and consequently the spectral spreading. Also, it is utilized to decrease the sensitivity towards frequency errors and so, reducing system BER.

D. *Pulse Shaping Technique*

The peak power is present within the signal main lobe, whereas the ICI power is present with side lobes. So, the objective is to reduce the amplitude of side-lobes and increase the width of main lobe. This is done through using a new pulse shaping functions to reduce the side lops in each carrier and consequently, reduce the ICI [18].

This technique is very similar to the windowing technique, and even is implemented in similar ways, but their purposes are different. The pulse shaping means choosing a pulse with the desired spectral and orthogonality properties for ICI power reduction.

Several pulse shaping functions are present to perform the requirement as: Raised Cosine pulse (RC), and Square Root Raised Cosine pulse (SRRQ), which presented in equation (9) and (10) respectively:

$$P_{RC}(f) = \mathrm{sinc}\,(f\,t)\,\frac{\cos(\pi\,(\pi f t)}{1-(2\alpha f t)^2} \tag{9}$$

where

α, f, t roll off factor, frequency, and time respectively

$$P_{SRRC}(f) = sinc\,(f\,t)\left(\frac{4\,\alpha}{\pi-(f)^{0.5}}\cos(1+\ \alpha)\left(\frac{\pi f}{t}\right)\right) + \left(\frac{\frac{t}{4\alpha f}\sin(1-\alpha)\frac{\pi\alpha}{t}}{1-(4\alpha f/t)^{0.5}}\right) \tag{10}$$

Through this technique, side loop power is decreased to a reduce the ICI between the adjacent carriers and achieve better bandwidth efficiency, which could be further enhanced through increasing the number of filter coefficients, as, indicated in previous literature [19].

V. System Model

The proposed MIMO-RNS-OFDM system is shown in Fig. 4 is initialized with a binary data random source, converted to residue system. The resultant packet is then modulated, coded through the Space-Time Block Coding (STBC) encoder, passed to a Serial-To-Parallel (S/P) converter for parallel transmission, passed through an IFFT block, and finally transmitted through the antenna. At the receiver side the communication blocks are the reverse of the transmitter.

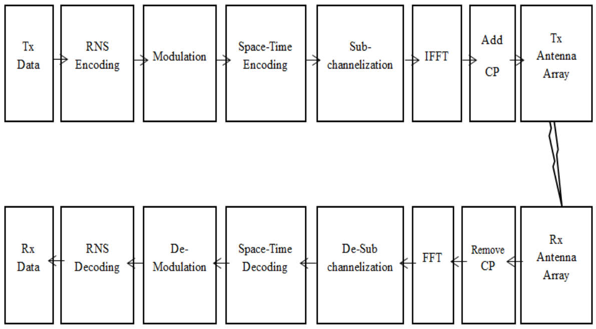

Fig. 4. MIMO-OFDM system model

The above system shown in Fig. 4; is evaluated by measuring the Carrier-Interference-Ratio (CIR) given in equation (11), and the Bit Error Rate (BER) of the signal shown in equation (12), respectively.

$$\mathrm{CIR} = \frac{|S(k)|^2}{\sum_{l=0,l\neq k}^{N-1}|S(l-k)|^2} \tag{11}$$

where;

S(l-k) Complex coefficient for ICI components in the receiving signal.

And; the probability of error for M-PSK modulated transmission is given by:

$$\mathrm{PERR} = \gamma \sum_{k=1}^{\min(2,\lceil\frac{M}{4}\rceil)} Q\left(\sqrt{2\sigma\, x}\,\sin\left(\frac{(2k-1)\pi}{M}\right)\right) \tag{12}$$

$$\gamma = \frac{2}{\max(\log 2\ M,2)} \tag{13}$$

where;

M; The constellation size

ρ; The SNR per symbol

x; Is a chi-square distributed random variable

VI. Simulation Results

The results obtained from the MATLAB simulations are discussed, where various analysis had been performed on MIMO-RNS-OFDM system to measure its resilience towards ICI in comparison to current MIMO-OFDM systems.

In this simulation, 1000 symbols are 512-QAM modulated and transmitted over a MIMO-OFDM communication system using RNS coding technique with redundant moduli's (17, 13, 11, 7, 5, 3), were (11, 7, 5, 3) are the information moduli's and the set (13, 17) are the redundant moduli's.

A. Offset effect on MIMO-RNS-OFDM System

The performance of communication system in the presence of frequency offset between the transmitter and the receiver is seen in Fig. 5.

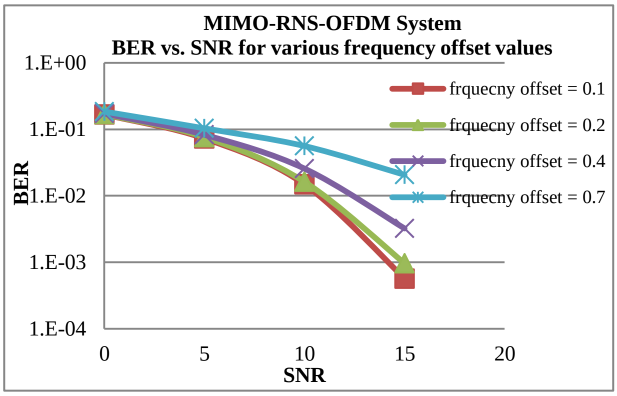

Fig. 5. Effect of frequency offset on System Performance

In Fig. 5, it is shown the degradation in performance when increasing the frequency offset. Thus, when the offset is small, the system has a lower BER (better).

B. ICI Measurements for MIMO-RNS-OFDM System

For a pre-defined SNR value (80), the transmission signal error is plotted versus the frequency offset as seen in Fig. 6 for OFDM system with and without RNS moduli's (13, 11, 7, 5, 3) as coding scheme;

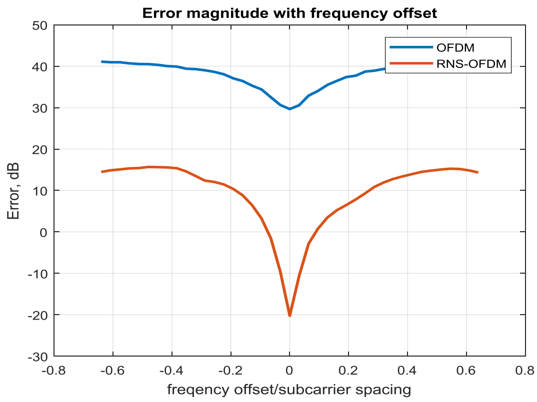

Fig. 6. Error for MIMO-RNS-OFDM system

Where; it is seen in Fig. 6 an absolute 25dB improvement when using the RNS scheme, which is better than the achieved improvement using ICI cancelation scheme indicated in section (4.A).

In addition, it is seen that - as expected - as the frequency offset increase this would increase the error due to the increasingly loss of orthogonality between inter-carriers.

C. ICI Measurements for MIMO-RRNS-OFDM System

Using RNS technique with redundant moduli's (17, 13, 11, 7, 5, 3), where (11, 7, 5, 3) are the information moduli's and the set (13, 17) are the redundant moduli's, and measuring ICI for the system comparing its value with the communication system without any redundant modus as seen in Fig. 7;

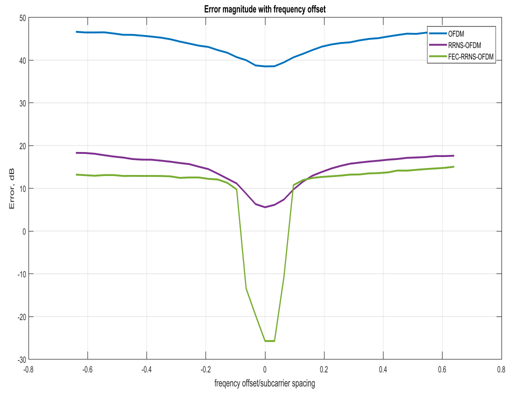

Fig. 7. Error for MIMO-RRNS-OFDM systems

Here; in Fig. 7 improvement is more than 30 dB, which is better than ICI cancellation scheme and RNS coding scheme seen in sections (4.A) and (6.B) respectively.

Moreover, the system exhibit similar performance as that shown when using RNS as a coding scheme only, as seen in section (6.B).

D. Effect of RNS Moduli Selection on ICI Performance

Increasing the order of RNS moduli set and measures the system performance to see the effect of the selection of the RNS on ICI reduction.

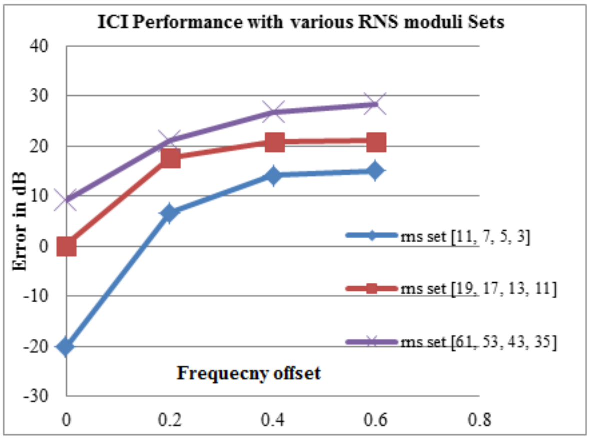

Fig. 8. ICI vs. RNS moduli set

From Fig. 8, it is noted that each time the amplitude of the RNS set increased this would increase the ICI error, and thus the increased signal amplitude would directly increase the interference between sub-carriers.

Now; in the comings sub-sections (E) to (H); various mitigation schemes are implemented and analyzed in the MIMO-RNS-OFDM communication system to study and evaluate its performance in combination with Residue coding technique.

E. MIMO-RNS with "Frequency Domain Equalization"

A frequency domain equalizer is used in the receiver, and the system performance is evaluated over a Rayleigh fading channel, as seen in Fig. 9.

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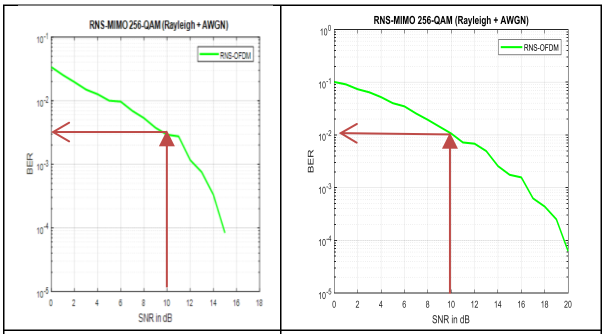


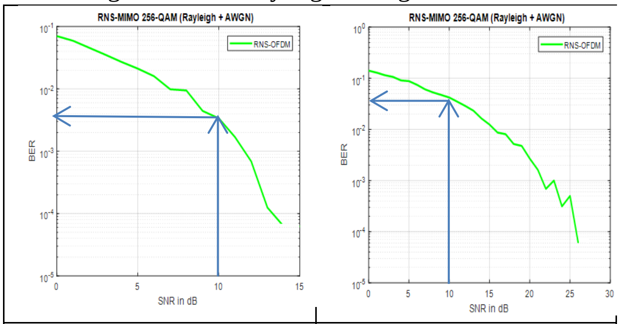
a) With Equalization | b) Without Equalization

Fig. 9. MIMO-OFDM RNS system with/without equalizer

where: at SNR = 10, BER for the communication system with error correction is $3*10^{-3}$ while it reaches $1*10^{-2}$ for the system without error correction.

F. *MIMO-RNS with "Self-Cancellation"*

Using data conjugate technique in self-cancellation scheme, where the system performance is evaluated as seen in Fig. 10 over a Rayleigh fading channel.



a) With mitigation | b) Without mitigation

Fig. 10. MIMO-OFDM RNS system self-cancellation scheme

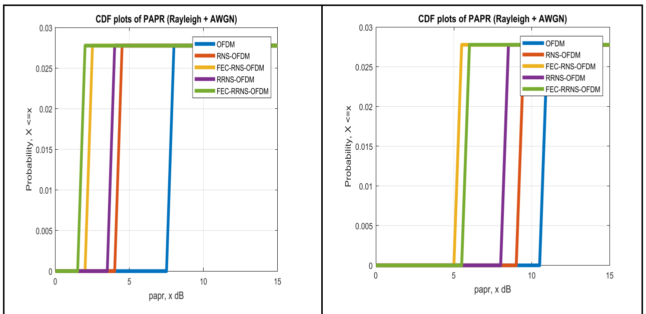
where; at SNR =10, BER for the communication system with error correction is $4*10^{-3}$ while it reaches $4*10^{-2}$ for the system without error correction.

G. *MIMO-RNS with "Pulse Shaping"*

A raised cosine pulse shaping scheme added to the MIMO-RNS-OFDM system, and evaluated through the coming simulations.

1) *PAPR measurement*

Perform recurrent measurement to evaluate the PAPR of the communication system with and without pulse shaping mitigation scheme as seen in Fig. 11.



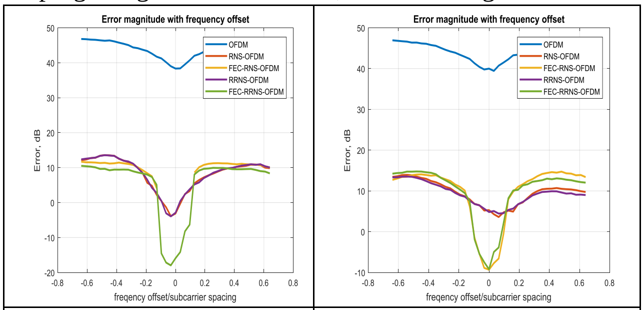
a) With mitigation scheme | b) Without mitigation scheme

Fig. 11. PAPR analysis for MIMO-RNS-OFDM with pulse shaping

From Fig. 11a and 11b, it is shown that reduction in PAPR seen over different wireless communication systems when using pulse shaping mitigation scheme in comparison to that without the mitigation scheme.

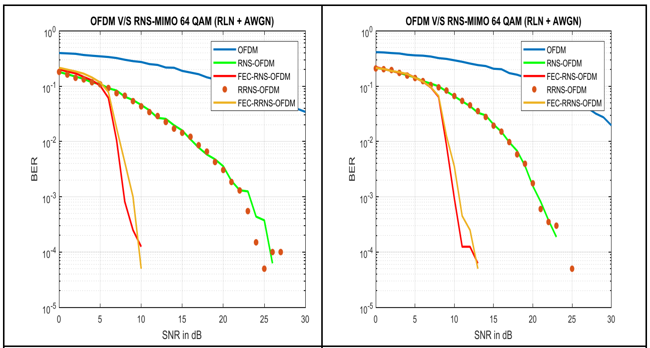
2) *ICI and BER measurement*

Then measuring the ICI error and overall BER performance for the system with and without pulse shaping mitigation is measured, as seen in Fig. 12 and 13.



a) With mitigation scheme | b) Without mitigation scheme

Fig. 12. ICI analysis for MIMO-RNS-OFDM with pulse shaping



a) BER With pulse shape | b) BER Without pulse shape

Fig. 13. BER analysis for MIMO-RNS-OFDM with pulse shaping

From the above Fig. 12a, using the mitigation scheme with RNS coding the ICI is reduced around 40 dB while without the mitigation scheme as seen in Fig. 12b the reduction is only 30 dB. The improved features seen in Fig. 12a is attributed to the use of pulse shaping scheme as a mitigation technique in the communication system.

And from Fig. 13 the BER performance for the system with and without mitigation scheme is measured, it is shown that BER performance in Fig. 13a is better than that seen in Fig. 13b. Where, at SNR = 10 dB, the BER for the RRNS communication system with mitigation scheme seen in Fig. 13a is 10^{-4} while for the same system without mitigation scheme as seen in Fig. 13b is 10^{-3}.

This result is coherent with that obtained in Fig. 13 indicating the decrease of ICI when implementing mitigation scheme.

H. *MIMO-RNS-OFDM vs. ICI Reduction Techniques*

In this subsection a comparisons of various ICI cancelation schemes that are implemented within the MIMO-RNS-OFDM system are studied and analyzed as seen in Fig. 14, to determine the best choice of ICI mitigation techniques that is suitable of RNS coding scheme.

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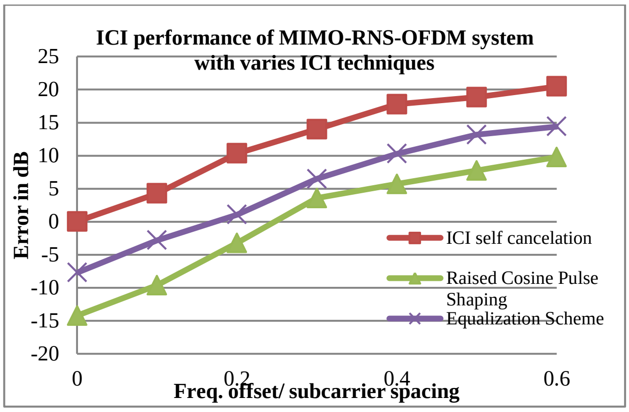

Fig 14. a: ICI for MIMO-RNS-OFDM with varies mitigation schemes

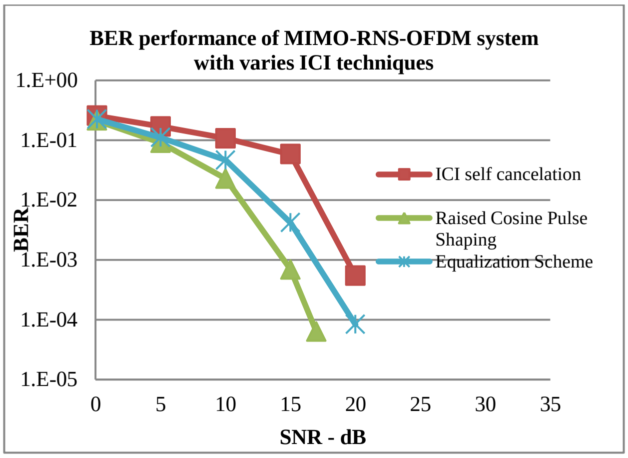

Fig 14. b: BER for MIMO-RNS-OFDM with varies mitigation schemes

The ICI and BER seen in Fig. 14 improve when utilizing a mitigation technique with the proposed RNS coding scheme. Some mitigation techniques have better performance as compared to others, where the Raised cosine pulse shaping provide better performance compared to that when using the equalization scheme; through maintaining less ICI and better bandwidth efficiency.

VII. Conclusion

In this paper, a review for MIMO-OFDM system performance using ICI self-cancelation, pulse shaping, windowing mitigation techniques had been provided and discussed.

An RNS coding insertion in MIMO-OFDM communication system has been proposed, and evaluated with respect to both CIR and BER performance. The usage of residue system had showed its advantage in improving the communication system features through decreasing the ICI and improving the BER performance.

The MIMO-OFDM with RNS coding scheme further enhanced through the insertion of ICI mitigation technique in the communication system, where the pulse shaping mitigation scheme had proven its enhanced performance with the residue system over the equalization scheme; through the recorded improvement in the BER, PAPR and ICI parameters.

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