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CARRIER FREQUENCY SYNCHRONIZATION FOR FREQUENCY DOMAIN INDEX MODULATED OFDM SYSTEMS

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Abstract

With next generation of wireless communication systems being conceptualised with new applications, smart devices and use cases which demand unprecedented levels of high data rates,spectral efficiency, reliability ,low latency andwith high energy efficiency.The Index modulated Orthogonal frequency division multiplexing (OFDM-IM) stand out as the most endearing physical layer modulation technique capable of providing greener communications. However, OFDM-IM is also very sensitive to frequency synchronization errors similar to classical OFDM and needs to be addressed on priority. In this article a novel algorithm is proposed which estimates and correctsthe introduced carrier frequency offset during transmission using the remodulated guard interval period (cyclic prefix) which is inherent to every symbol transmitted and the algorithm’s performance is compared to that of Yang’s algorithm in two variants of OFDM-IM and we show that our algorithm gives better performance and it is independent of any frequency domain IM schemes.

Index Terms — CFO,CP, ESIM, FD-IM, GIM,OFDM-IM,RF-Impairment

1. INTRODUCTION

OFDM is an inherent modulation technique employed in most of the mobile and wireless communication standards and systems [1] such as Third Generation Partnership project (3GPP) 5G New radio (NR), IEEE 802.11 WLAN standards like 11a/11g/11n/11ac and 11ax Wireless Fidelity (Wi-Fi), Long term Evolution (LTE), Worldwide interoperability for Micro wave access (WiMAX) Technology IEEE 802.16d/e, HIPERLAN/2 [2],[3],[4],[5],[6]. It has successfully flourished in all these systems owing to its merits of high data rate, effective resistance towards interference, simple single tap frequency domain equalization. However, the OFDM technique is limited by high peak to average power ratio (PAPR), sensitivity to timing and frequency errors [7].

The emerging next Generation of wireless networks (5G and beyond)are being designed with exceptionallevels of very high data rates,reliability, low latency and the urgent need to transit for greener communications with ubiquitous use cases in the escalating teletraffic scenario has given rise to the challenging prospects in the research arena for advanced modulation schemes and waveformswhich are more

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efficient in terms of both spectrum and energy with reliability [8],[9],10].Orthogonal frequency division multiplexing with index modulation (OFDM-IM), similar to classical OFDM is a physical layer multi-carrier transmission technique with sparse symbol mapping has garnered a lot of research interest in both Industry and academia [11]. The Index Modulation (IM) extends the concept of spatial modulation in the frequency domain providing an additional index dimension with amplitude and phase constellation symbol to carry more data which leads to additional diversity gain [12]. This flexible structure of IM enables to create more energy friendly transmission signals which is the utmost desirable attribute [13]. Thus incorporating IM with OFDM results in OFDM-IM, The main idea in this technique is to utilise only a subset of the subcarriers and its indices to carry the data symbols while the rest are not used.This technique in general saves the transmitted power and the bit error rate (BER) performance is improved in comparison to classical OFDM [14] .The high PAPR is also one of the critical aspect in OFDM systems since it not only degrades the performance efficiency of the transmitter power amplifier but also reduces the signal to quantization ratio in Analog to Digital (A/D) and Digital to Analog (D/A) converter, which can be addressed efficiently in OFDM-IM [15],Since only partial subcarriers are used to carry the data and the indices of these tones carrying additional data are extracted without any energy utilization, OFDM-IMtechnique enhances the system capability to attain the same throughput as classical OFDM by employing only partial resources.

The subcarriers in OFDM-IM are categorised into two types as data or active subcarriers and unused or inactive subcarriers, with active indices exploited to implicitly convey information bits [16]. However, OFDM-IM being a multi-carrier system similar to a classical OFDM, It has inherited the sensitivity towards the carrier frequency offset, Any frequency error present distorts the orthogonality between the subcarriers resulting in inter carrier interference (ICI) which has double penalty effects of not only reducing the amplitude levels but also degrading the system performance [17].

It is well known fact that effective CFO estimation and compensation techniques are critical to a multi carrier system. Any algorithm to be designed needs to meet the standard prescribed limits [18]. The CFO compensation techniques are broadly classified as data aided (utilising the training/synchronization sequences or pilot sequences) and data unaided. In this paper we are proposing a blind method to effectively eliminate the CFO introduced.

cyclic prefix or the guard interval (CP) are inherent to every OFDM symbol and its lengthgenerally varies anywhere between 25% to 3.125% of the NFFT length (0.4 or 0.8 or 1.6 or 3.2 μs of the symbol time according to 11a/11g/11n/11ac/11ax WLAN standards) [19], The CP structure as it is can be utilised to find the CFO only when the channel experiences flat fading where the cyclic structure of the CP is not contaminated and the repetitive structure is intact. But in a frequency selective fading channels the CP cannot be directly utilised to find the CFO, since the selective

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fading channel environment would have destroyed the cyclic structure of the guard interval [20].

Frequencysynchronization impairment has been extensivelystudied in OFDM systems resulting in awide range of CFO detection andcompensation methods utilizing both data aided and blind approaches [21], [22], [23], [24] and [25]. Even though a plethero of research have been carried out and published in the areas of OFDM-Index Modulation which confirms the advantages of OFDM-IM in comparison to classical OFDM,giving considerateamount of potential applications, advantages and working principle [26], [27],[28], [29], [30], [31], [32], [33], [34], [35], [36]but most of the prevailing IM techniques are only assessedunder ideal conditions and further very few research has been done on the impact of carrier frequency offset on its performance. In this work, error performance of 2 important frequency domain IM schemesenhanced subcarrier index modulation (ESIM) and generalized index modulation (GIM)[37] are evaluated with the proposed and yang's algorithm in the presence of CFO.

The author'syang and Chen [38], have come up with CFO estimation technique for the OFDM-GIM variant using the pilot and the unused data tones. Initially the CFO is estimated using the preassigned pilot tones and later the unused data tones in GIM-OFDM is detected using energy detection and then utilising both the pilot and unused data tones the CFO is re-estimated. The major drawback of this technique lies in the detection of the unused data tones which vary in number and position of each sub block and any detection of an active data tone as inactive data tone results in additional errors and the threshold used in the energy detection varies with the SNR and needs to be properly chosen and since this algorithm also depends on preassigned pilot subcarriers reduces the spectral efficiency.

Q. Ma, P. Yang[39], have come up with a theoretical approach to predict the BER performance of OFDM IM schemes like OFDM Interleaved subcarrier index modulation (OFDM ISIM) and OFDM adjacent subcarrier index modulation(OFDM ASIM) in comparison to classical OFDM under the influence of CFO and Rayleigh fading channels but they do not provide any correction mechanism for the CFO.A. Tusha, S. Doğan[40],have demonstrated bit error rate performance against the varying SNR for frequency domain IM schemes of GIM and subcarrier index modulation (SNM) in the presence of RF Impairments like CFO and IQ Imbalance and have shown through computer simulations that even though the IM scheme provide higher spectral efficiency but they are sensitive to RF Impairment like CFO and IQ Imbalance like classical OFDM systems and no method are suggested to overcome these RF Impairment.The authorsS. Dang, G. Ma [41] propose a more precise analytical results related to the error performance analysis methodology for OFDM-IM based on Craig's formula instead of the exponential approximation where they have derived the average block error rate (BLER) and BER in closed form. But they don't consider any of the RF Impairments into consideration when plotting average BLER and BER with respect to ratio of transmit power to noise power (P_t/N_o).The authors M. Wen, X. Cheng [42] have studied the achievable rate with an

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M-ary constellation of OFDM-IM in the presence of gaussian noise and with the knowledge of complete channel state information known at the receiver , they have also come up with an interleaving technique applied to the subblock grouping in OFDM-IM which exploits the diversity gain better in a frequency selective fading channel and hence IM outperforms the conventional OFDM systems under small M (PSK schemes rather than QAM modulation techniques) and for certain ranges of signal to noise ratio.

In [43], the authors M. Wen, E. Basar have come up with multiple mode transmission scheme (MM-OFDM-IM)) wherein the multiple subcarriers can transmit different modes and additional data bits are carried through permutation of the multiple modes. They have also proposed a detector based on subcarrier wise detection. But the major drawback of this scheme comes in the presence of CFO impairment as a strong ICI will be experienced similar to OFDM since all the subcarriers are filled with non-zero values, and no scheme to mitigate the ICI is proposed.In [44],J. Seo, J. Joo, have analysed the performance of ESIM OFDM using Schmidt and cox algorithm synchronizer in the presence of AWGN and rayleigh fading channel and have come up with the threshold selection but it is not dependent on Eb/No and doesn’t address the synchronization issues.

The authorsY. Shi, X. Lu[45] yet again propose a new variant of OFDM Index Modulation titled OFDM with all index modulation (OFDM-AIM) wherein the symbol bits used in OFDM IM is eliminated by replacing the PSK/QAM constellation modulator by subblock modulator and they suggest that to accomplish the high diversity gain, the subblocks with higher order set design must be utilised and they propose an algorithm to construct the subblocks set with maximum order diversity. In [46],J. Mrkic and E. Kocan have come up with the hybrid OFDM-IM,wherein the mode can be switched between the conventional OFDM and OFDM-IM based on the channel conditions. If the SNR values ranges from low to medium range then normal OFDM is used for transmission and when the SNR is high OFDM-IM is used .In both the cases for simulations Rayleigh and Rician fading channels is considered while plotting BER vs. SNR, no other RF impairment is considered.

Against the above background, In this paper we have come up with a novel CFO algorithm which estimates and compensates the frequency error and the performanceis compared with the existing yang’s algorithm [38], the simulation results shows that the proposed method is irrespective of the modulation technique used and performs very well as long as the guard interval is greater than the channel’s maximum delay spread and as the guard length reduces the performance of the algorithm also reduces.

The rest of the sections in the article are structured asmentioned. The system model of OFDM-IM is explained with illustration in section 2, theproposed detection algorithm is described in section 3, the simulation and results are discussed in 4^{th}section, while the paper is concluded in section 5.

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Notation: In this article the symbols P^T, P^* and $P^‡$ represent the transpose, complex conjugate and conjugate transpose respectively and E{u} denotes the expectation operator.

2. OFDM-IM SYSTEM MODEL

IM technique can be utilised in the time domain, frequency domain, spatial domain or the code domain on time slots, subcarriers, antennas and channel state variations respectively. In this work we mainly concentrate on the 2 important schemes in frequency domain index modulation (FD-IM), ESIM-OFDM and GIM-OFDM to demonstrate our algorithm performance. Block schematic of frequency domain OFDM-IM systems is depicted in the Fig.1. The FD–IM is capable carrying the extra data bits particularly on the locations or indices of the activated data tones without

the need of the additional energy for transmission.

The ‘s’ data bits to be carried by the symbol is fed to a bit splitter which equally splits the s bits into G groups where each group is allotted a set of p bits which are further segregated into two subgroups of index bits(p1) and symbol bits(p2). The index bits determines the positions of the data tones which carries the data symbols which are

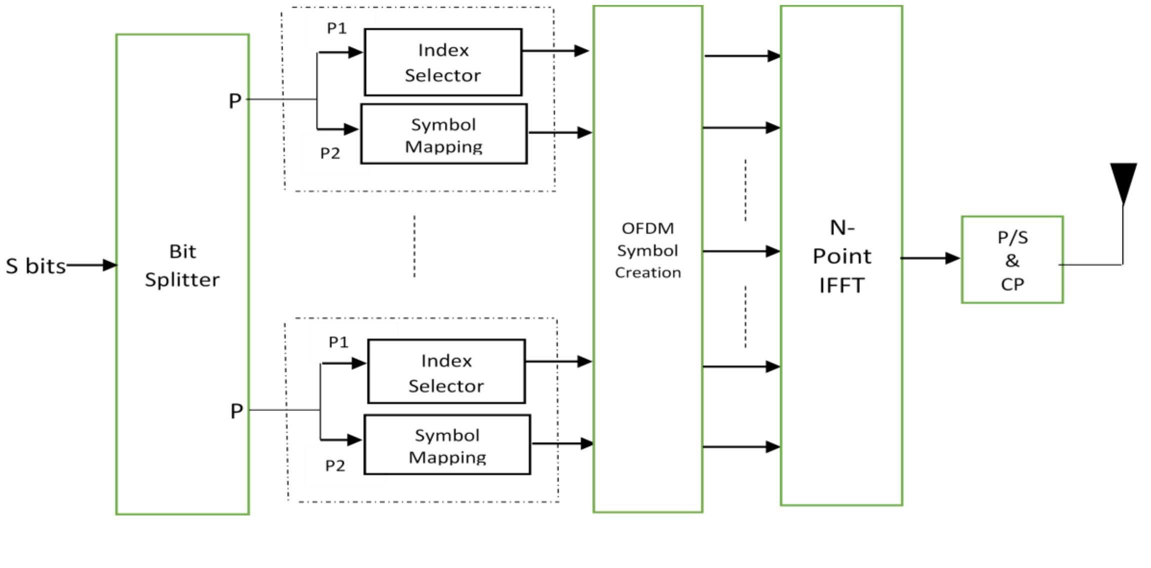

Fig. 2: Block-Scheme of OFDM IMSystem

generated using the data bits from symbol mapping, and later all these subgroups are concatenated and fed to a OFDM symbol formation block which creates the OFDM symbol and passed to the N-IFFT block resultingin a time domain signal of N samples to which a sufficient length guard interval is pre-appended based on the maximum channel delay spread time.

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In enhanced subcarrier index modulation OFDM (ESIM-OFDM), the subcarriers are grouped using 2 successive data tones and in every group only one data tone is activated and the other one is kept as unused subcarrier and the indices of these used data carrier carries the additional data .

In the GIM frequency domain IM technique, the data tones grouped into OFDM subgroups are not restricted to 2, In every OFDM subgroup of size p, it is further split intoindex bits represented as p1 and symbol bits (p2) . Index bits specify the locations of the activated data tones which carry the mapped symbol bits (m1 and m2) explicitly and the other data tones are retained as unused data subcarrier (u1 and u2) as shown in the look up Table 1 where p1 is chosen to be 2 and subgroup size is 4 .

TABLE 1

LOOK UP TABLE FOR GIM-OFDM

Index bits	Data Location	subgroups
[0,0]	[1,2]	[m1,m2,u1,u2]
[0,1]	[2,3]	[u1,m1,m2,u2]
[1,1]	[1,4]	[m1,u1,u2,m2]
[1,0]	[3,4]	[u1,u2,m1,m2]

Let $\boldsymbol{x}_i$ be the input data vector of length N, and $\boldsymbol{x}_{i,L}$be the guard interval of length L which is pre-appended to the $\boldsymbol{x}_i$input vector block making the transmitted signal cyclic in nature.

$$\boldsymbol{x}_i = [x_i(0), x_i(1), x_i(2), \ldots \ldots \ldots \ldots \ldots x_i(N-1)]^{\mathrm{T}} \quad (1)$$

$$\boldsymbol{x}_{i,L} = [x_i(N-L), \ldots \ldots \ldots \ldots \ldots x_i(N-2), x_i(N-1)]^{\mathrm{T}} \quad (2)$$

Then the i^th signal vector transmitted can be mathematically represented as

$$\boldsymbol{t}_i = \begin{bmatrix} \boldsymbol{x}_{i,L} \\ \boldsymbol{x}_i \end{bmatrix} \quad (3)$$

The i^{th} signal block captured at the receiver end can be represented as

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$$\boldsymbol{y}_i = \boldsymbol{H}\begin{bmatrix}\boldsymbol{x}_{i-1,L}\\ \boldsymbol{x}_i\end{bmatrix} e^{j2\pi\frac{i(N+L)\varphi}{N}}\boldsymbol{D}(\varphi) + \boldsymbol{w}_i \quad (4)$$

Where $\boldsymbol{H}$ is a Toeplitz matrix of size (N+L) x (N+2L) with first row as $[h(L), \dots \dots.., h(0), 0 \dots 0]$, first column is $[h(L), 0, \dots \dots..0]^T$ and the channel coefficients are represented as h(0),h(1),h(2),…….h(L). The normalized carrier frequency offset $\varphi$is defined as the product of NΔf/Fs, where Δf is the CFO(Hz) and $F_s$is the sampling frequency.

The diagonal matrix **D**(φ)and AWGN vector$\boldsymbol{w}_i$ of the i[th] noise block with variance of σ_i^2 are given as in equation (5) and (6)

$$\boldsymbol{D}(\varphi) = diag\{1, e^{\frac{j2\pi\varphi}{N}}, \dots \dots \dots, e^{\frac{j2\pi(N+L-1)\varphi}{N}}\} \quad (5)$$

$$\boldsymbol{w}_i = [w_i(0), w_i(1), \dots \dots \; w_i(N+L-1)]^T \quad (6)$$

3. PROPOSED CFO ESTIMATION ALGORITHM

A remodulated vector $\widetilde{\boldsymbol{y}}_i$may be created by using 2 received OFDM-IM symbols (current received symbol $\boldsymbol{y}_i$ and the previous received symbol $\boldsymbol{y}_{i-1}$ .When the last N samples of the previous symbol is appended with the initial L entries of current symbol a remodulated signal vector is constructed and its length is also equal to a conventional OFDM symbol length of N+L. and its cyclic structure is retained and can be utilised even in a multipath environmentas proved by the authors F. Gao, Y. Zeng, A. Nallanathanin [47] . The remodulated vector can be represented mathematically as in equation (7)

$$\widetilde{\boldsymbol{y}}_i \triangleq [\tilde{y}_{i-1}(L), \dots \tilde{y}_{i-1}(N+L-1), \tilde{y}_i(0), \dots \tilde{y}_i(L-1)]^T \quad (7)$$

The constructed remodulated signal vector at the receiver impaired with channel, carrier offset and noise can be represented as

$$\widetilde{\boldsymbol{y}}_i = \boldsymbol{H}\begin{bmatrix}\boldsymbol{x}_{i-1}\\ \boldsymbol{x}_{i,L}\end{bmatrix} e^{j2\pi\varphi\frac{i(N+L)-N}{N}}\boldsymbol{D}(\varphi) + \widetilde{\boldsymbol{w}}_i \quad (8)$$

Where ,$\widetilde{\boldsymbol{w}}_i = [w_{i-1}(L), \dots w_{i-1}(N+L-1), w_i(0), \dots w_i(L-1)]^T$.

Computing the autocorrelation matrix $\mathbf{R}_{rr}$ (ε) of the difference vector $\boldsymbol{r}_i(\varepsilon)$ where the variable ε is utilised in the offset calculation.

$$\mathbf{R}_{rr}(\varepsilon) = E\{\boldsymbol{r}_i(\varepsilon)\boldsymbol{r}_i(\varepsilon)^{\ddagger}\} \quad (9)$$

And the difference vector$\boldsymbol{r}_i(\varepsilon) = \boldsymbol{y}_i - e^{j2\pi\varepsilon}\widetilde{\boldsymbol{y}}_i$, substituting the equations (4) and (8) in $\boldsymbol{r}_i(\varepsilon)$ can be represented as

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$$\boldsymbol{r}_i(\varepsilon) = e^{j2\pi i\frac{(N+L)\varphi}{N}}\boldsymbol{D}(\varphi)\,\boldsymbol{H}\left(\begin{bmatrix}\boldsymbol{x}_{i-1,L}\\ \boldsymbol{x}_i\end{bmatrix} - e^{j2\pi(\varepsilon-\varphi)}\begin{bmatrix}\boldsymbol{x}_{i-1}\\ \boldsymbol{x}_{i,L}\end{bmatrix}\right) + \underbrace{\left(\boldsymbol{w}_i - e^{j2\pi\varepsilon}\widetilde{\boldsymbol{w}}_i\right)}_{\eta} \quad (10)$$

Using equation (10), the auto correlation matrix Rrr (ε) is computed assuming that signal vector and the noise vector both are uncorrelated

$$\boldsymbol{R}_{rr}(\varepsilon) = \sigma_x^2\boldsymbol{D}(\varphi)\boldsymbol{H}\boldsymbol{\varpi}\boldsymbol{H}^{\ddagger}\boldsymbol{D}(-\varphi) + \sigma_{\eta}^2\boldsymbol{R}_{\eta}(\varepsilon) \quad (11)$$

Whereϖ is a matrix of size (N+2L) x (N+2L) represented by (11a) and with$\tau_1 = \cos\big(2\pi(\varepsilon-\varphi)\big)$and $\tau_2 = 1 - e^{j2\pi(\varepsilon-\varphi)}$ and $R_{\eta}(\varepsilon)$ is a matrix of order (N+L) x (N+L) given in (11b), and the average signal power of the vector transmitted is σ_x^2

$$\boldsymbol{\varpi} = \begin{bmatrix} 2(1-\tau_1)I_L & 0 & 0 & \tau_2^* I_L & 0 \\ 0 & 2I_L & 0 & 0 & \tau_2^* I_L \\ 0 & 0 & 2I_{N-2L} & 0 & 0 \\ \tau_2 I_L & 0 & 0 & 2I_L & 0 \\ 0 & \tau_2 I_L & 0 & 0 & 2(1-\tau_1)I_L \end{bmatrix} \quad (11a)$$

$$\boldsymbol{R}_{\eta}(\varepsilon) = \begin{bmatrix} 2I_L & 0 & -e^{-j2\pi\varepsilon}I_L \\ 0 & 2I_{N-L} & 0 \\ -e^{-j2\pi\varepsilon}I_L & 0 & 2I_L \end{bmatrix} \quad (11b)$$

The diagonal entries of $R_{rr}(\varepsilon)$are computed using the equation (11) and can be represented as

$$[\boldsymbol{R}_{rr}(\varepsilon)]_{k,k} = \begin{cases} 2(\zeta - \alpha_1\zeta_k) & if\ i \in C \\ 2\zeta + (2\sigma_{\eta})^2 & otherwise \end{cases} \quad (11c)$$

Where C is the set of indices of first L (0, 1. . . L-1) and the last L samples (N, N+1 . . . N+L-1) of the difference vector r_i

$$\zeta \triangleq (\sigma_x)^2\sum_{l=0}^{L}|h(l)|^2 \quad (12)$$

$$\zeta_k = \begin{cases} (\sigma_x)^2\sum_{l=k+1}^{L}|h(l)|^2 & if\ 0 \le k \le L-1 \\ (\sigma_x)^2\sum_{l=0}^{i-N}|h(l)|^2 & if\ N \le k \le N+L-1 \end{cases} \quad (13)$$

It is clear from equation (12) and (13) that bothζ and ζ_k are independent of parameters ε and φand the costfunction can be written as

$$\tilde{J}(\varepsilon) = \sum_{k\in C}[\boldsymbol{R}_{rr}(\varepsilon)]_{k,k} \quad (14)$$

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Hence the cost function is minimum when ε is equal to φ . And the closed form solution to the efficient estimation of the CFO can be approximated in terms of autocorrelation matrix $\mathrm{R_{rr}}(\varepsilon)$ as equation (15) and S is the no. of OFDM-IM symbols considered. Here only S-1 symbols are considered as a minimum of 2 OFDM-IM is required to construct one remodulation vector.

$$\boldsymbol{R}_{rr}(\varepsilon) \approx \frac{1}{S-1}\sum_{i=1}^{S-1}\boldsymbol{r}_i\,(\varepsilon)\big(\boldsymbol{r}_i\,(\varepsilon)\big)^{\ddagger} \qquad (15)$$

$$\boldsymbol{R}_{rr}(\varepsilon) \approx \frac{1}{S-1}\sum_{i=1}^{S-1}\sum_{k\in C}\left(\boldsymbol{r}_i\,(k) - e^{j2\pi\varepsilon}\tilde{\boldsymbol{r}}_i(k)\right)\left(\left(\boldsymbol{r}_i\,(k) - e^{j2\pi\varepsilon}\tilde{\boldsymbol{r}}_i(k)\right)^{*}\right) \qquad (16)$$

The range for ε is set between (-0.5,0.5) and the cost function can be rewritten as

$$\hat{\varphi} = \arg\min_{\varepsilon\in(-0.5\,,0.5)} \tilde{J}(\varepsilon) \qquad (17)$$

The minimum of the cost function is attained by taking the derivative of $\tilde{J}(\varepsilon)$with respect to ε and equating to zero. It is observed that for the range between [-0.5, 0.5], equation (16) has unique minimum and Level 1 estimate for the CFO estimation is given by

$$\hat{\varphi}_{L1} = \frac{1}{2\pi} angle \;\left[\sum_{i=1}^{S-1}\sum_{k\in c}\boldsymbol{y}_i(k)\big(\tilde{\boldsymbol{y}}_i(k)\big)^{*}\right] \qquad (18)$$

Once the Coarse estimate is obtained, evaluatethe equation (11c) and select only those indices within the 2L length of the set C of the diagonal entries with minimum value such that the new length of Cmin<2L , Since the smaller diagonal entries have larger second order derivative. After choosing the Cmin, compute the Level 2 estimate using the equation (19)

$$\hat{\varphi}_{L2} = \frac{1}{2\pi} angle \;\left[\sum_{i=1}^{S-1}\sum_{k\in Cmin}\boldsymbol{y}_i(k)\big(\tilde{\boldsymbol{y}}_i(k)\big)^{*}\right] \qquad (19)$$

The mean square error (MSE) is finally computed by taking the mean square difference between the computed offset and the introduced offset.
R dictates the number of runs the algorithm is computed.

$$\mathrm{MSE}(\varphi) \;= \frac{1}{R}\sum_{i=1}^{R}|\hat{\varphi}(i) - \varphi\,|^2 \qquad (20)$$

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4. SIMULATION RESULTS AND DISCUSSIONS

The computer simulations were carried out using Matlab software, the performance evaluation were carried out for 2 variants of Frequency domain Index variant namely the ESIM-OFDM and GIM-OFDM. The simulation parameters chosen are listed in Table 2.

TABLE 2

SIMULATION PARAMETERS

PARAMETERS	**GIM**	**ESIM**
FFT size (N)	64	64
Guard Interval (CP Length)	16 / 8	16/8
No. of subgroups in every symbol	16	32
Modulation type	BPSK	BPSK
Normalized CFO	0.25	0.25
Channel	AWGN with Multipath Rayleigh fading	AWGN with Multipath Rayleigh fading
channel delay samples locations	[0,1,2,6,8]	[0,1,2,6,8]
channel tap power profile	[0.34,0.28,0.23,0.11,0.04]	[0.34,0.28,0.23,0.11,0.04]
No. of OFDM symbols (S)	50	50
No. of Runs	1000	1000

It is observed from Fig.2 that the performance of our proposed algorithm fares better in comparison to the algorithm proposed by yang's algorithm[38] using the unused data tones.In the yang's algorithm,even though the mean square errorof the CFO drops to 10^{-3} from 10^{-1} within the 3dB SNR, thereafter the MSE doesnot improve with the increase in the SNR and we see that the performance improves marginally till 30dB and thereafter we see a significant improvement in the MSE reaching more than the value of 10^{-6} and converging with the proposed algorithm. So, we observe that the algorithm utilising the unused subcarriers perform well at the high SNR

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regions. The proposed algorithm reaches MSE of 10^{-4} initially and with the increase in the SNR, we see an improvement to 10^{-6} around 25dB and with the further increase in the SNR we observe a marginal improvement in MSE to slightly greater than $10^{-6.}$

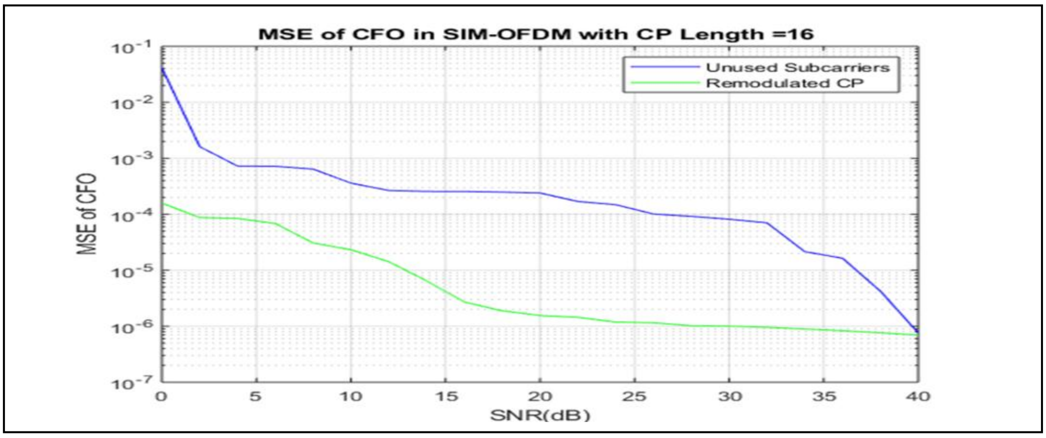

Fig. 2: Performance plot of SIM-OFDM: MSE of offset estimation Vs. Varying SNR

Fig.3 shows the performance comparison of MSE vs SNR for the case of GIM OFDM with CP length of 16 and the algorithm using the unused subcarriers. Yangs algorithm outperforms our proposed algorithm for SNR only greater than 38dB and till that SNR our proposed algorithm is superior and the MSE achieved better than10^{-6} while that of yangs reaches $10^{-7}$for SNR greater than 38.

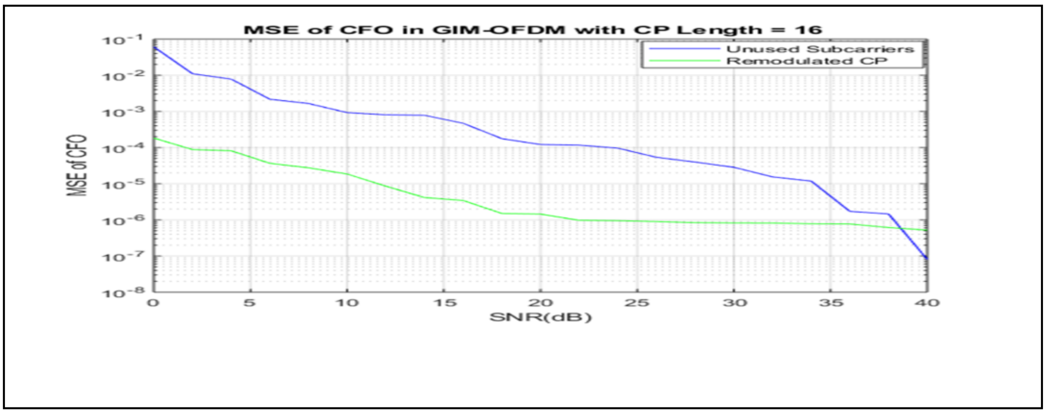

Fig. 3: Performance plot of GIM-OFDM: MSE of offset estimation Vs. Varying SNR

Fig.4 and Fig.5 gives the performance comparison between the proposed algorithm and the yangs algorithm for the SIM and GIM case but with reduced guard interval length by 50 % i.e the CP samples are reduced to 8 from 16. We observe that there is steep decrease in the performance of proposed algorithm and the MSE lies

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between 10-3 and 10-5 in both SIM and GIM OFDM. Whereas the yangs algorithm performance is unaffected by the change in the CP length and displays the same MSE as in Fig.2 and Fig.3 since it is independent of the guard interval.

Fig. 4: Performance plot of GIM-OFDM: MSE of offset estimation Vs. Varying SNR

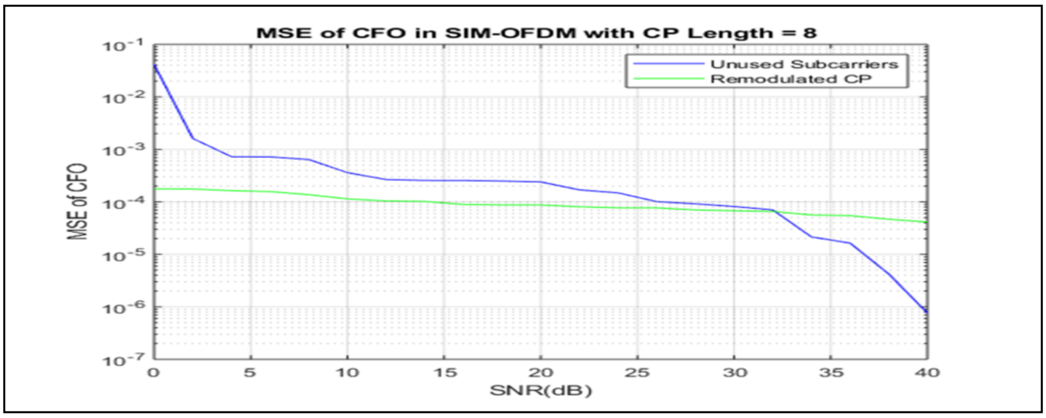

Fig. 5: Performance plot of GIM-OFDM: MSE of offset estimation Vs. Varying SNR

5. CONCLUSION

OFDM-IM is capable of addressing the critical need for a smooth transit to greener communications for 5G and beyond technologies .However it is sensitive to frequency errors which needs to be addressed efficiently for utilising its full potential. Our algorithm efficiently handles the frequency error by accurately estimating the CFO using the remodulated cyclic prefix. Like other CP based algorithm the remodulated CP is also of low complexity and it is independent of the modulation scheme employed or the variants of OFDM-IM used. The performance of the algorithm depends on the length of the CP and as the length reduces the performance degrades and saturates around 10^{-4}. This algorithm is most suited for

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the WLAN based systems as the length of the CP is sufficiently long to get accurate results and the performance can reach up to 10^{-7}.

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