Reduction of OFDM PAPR Using a Combined Hadamard Transformation and Selective Mapping for Terrestrial DAB+ System under Rayleigh and AWGN Channel

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Abstract—**This paper discusses a method for Peak to Average Power Ratio (PAPR) reduction in Orthogonal Frequency Division Multiplexing (OFDM). A Combination of Selective Mapping (SLM) and Hadamard Transformation (HT) as a simple and computational efficient technique for PAPR reduction in Orthogonal Frequency Division Multiplexing (OFDM) system is presented. In the proposed approach, Hadamard transformation was used in order to reduce the autocorrelation of data symbols which in turn reduces the resulting PAPR. Selective Mapping (SLM) was used to select an OFDM symbol with minimum Peak to Average Power Ratio (PAPR). The simulation results show that at the Complementary Cumulative Distribution Function (CCDF) of 4×10^{-3}, the PAPRof the proposed scheme is 5.84 dB. This marks an improvement of 4.26 dB when compared with PAPR of the original OFDM which is 10.10dB. On the other hand, the performance of our proposed scheme shows no significant Bit Error Rate (BER) deviation from that of the original data.**

Keywords—**Hadamard transform, Orthogonal Frequency Division Multiplexing (OFDM), Peak to Average Power Ratio (PAPR), selective mapping, Bit Error Rate (BER)**

I. INTRODUCTION

The Orthogonal Frequency Division Multiplexing (OFDM) as a multicarrier modulation scheme has found many applications especially in the field of wireless communication. Its ability to mitigate multipath and Doppler effects at high data rate transmission has made it a dependable Technology in wireless communication including the latest Digital Audio Broadcasting (DAB) systems. However, the major problem with OFDM among others is that it has high Peak to Average Power Ratio (PAPR). High peak to average power ratio leads to poor performance of High-Power Amplifiers (HPA) as it causes HPA to be operated outside their linear region and therefore cause signal distortion. Digital Audio Broadcasting (DAB) as a technology of interest in this article represents one of the modern forms of terrestrial radio broadcasting. It is a complex of technological innovations developed in the late 1980s as a part of the European Commission's investment program Eureka 147 [1]. DAB is intended to give good experience to listeners by giving quality audio sounds approximately to that of CDs and therefore replacing the existing Amplitude Modulation (AM) and Frequency Modulation (FM) audio broadcast services in future. It started with the traditional DAB and an improved version called DAB+ was introduced in February 2007. DAB+ is more efficient thanks to the use of a new audio codec (HE-AACv2 instead of MP2) and more robust thanks to the use of additional Reed-Solomon error correction coding [2]. DAB/DAB+ systems both are designed to cope with the problem of inter symbol interference caused by long echoes through the use of Orthogonal Frequency Division Multiplex (OFDM) as a multicarrier scheme. Orthogonal Frequency Division Multiplexing (OFDM) is a Frequency Division Multiplexing (FDM) of its own kind in which a single continuous large channel is divided into several narrow equally spaced parallel sub-channels each of them carrying low data rate stream on an orthogonal subcarriers [3]. OFDM is considered as trustworthy method for several wireless communication applications and obtained a lot of research interests [4]. This scheme has been adopted as a key technology for high data rate transmissions in many wireless applications and standards, e.g., Digital Audio Broadcast (DAB), Digital Video Broadcasting-Terrestrial (DVB-T), Digital Video Broadcasting Handheld (DVB-H), Wireless Local Area Network (WLAN), Worldwide

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Interoperability for Microwave Access (WiMAX), Long Term Evolution (LTE) and the Fifth Generation (5G) New Radio (NR), due to advantages of high spectral efficiency and immunity to multipath fading [5].

The rest of this paper is structured as follows: Section II gives a Literature survey. In Section III, an overview of OFDM is presented. Section IV presents the concept of PAPR in OFDM. The proposed technique for this article is discussed in Section V and Results are discussed in Section VI while Section VII gives the general conclusion.

II. Literature Survey

In spite of trustworthy and usefulness of OFDM scheme, one of the most cited drawbacks is that of having high Peak to Average Power Ratio (PAPR). High PAPR leads to inefficiency of the wireless communication system [6]. PAPR is the ratio of maximum power of a sample in an OFDM symbol to mean power of that OFDM symbol [3].

There are various methods proposed by different researchers in literature for OFDM PAPR reduction. Some of the popular methods used for OFDM PAPR Reduction are Iterative Clipping and Filtering (ICF) [7, 8], Coding Techniques [9, 10], Partial Transmit Sequence (PTS) [11], Selective Mapping (SLM) [12], Tone Injection (TI), Active Constellation Extension (ACE) [13], Tone Reservation (TR) and among others. Each of these methods has its strength and weakness especially when evaluated in terms of spectral and computational efficiencies.

The ICF is one of the popular and efficient PAPR reduction method where clipping and filtering mechanisms are iteratively applied to obtain the desired PAPR behavior [14]. In this method, signal with amplitude beyond a certain threshold is clipped. However, clipping process results into harmonic distortion caused by nonlinear input output characteristics of high-power amplifiers at higher signal power levels. Therefore, Filtering is applied to lower the amount of this distortion caused by clipping process. Another popular method for OFDM PAPR reduction is Selective Mapping (SLM). This technique is also widely used in OFDM systems to reduce PAPR as is known to have low signal distortion [11]. In this method, data symbols are multiplied with different phase vectors and then evaluated for PAPR. An OFDM symbol with lowest PAPR in the sample is selected for transmission. The phase vector corresponding to the selected symbol is also transmitted as Side Information (SI). The major drawback of SLM is that it needs transmission of Side Information (SI) (phase vector) to enable the receiver to decode the information. Transmission of Side Information (SI) leads to spectral inefficiency of the method. Also, the erroneous of SI will have strong effect to BER performance at the receiver [15].

Partial Transmit Sequence (PTS) [16] method and its improved version in [4] is also among of the well-known techniques for OFDM PAPR reduction without signal distortion.The basic idea of partial transmit sequence algorithm is to divide the original OFDM sequence into several sub-sequences and each sub-sequence multiplied by different weights until an optimum value is chosen [17]. An input data block is divided into many disjoint sub-blocks. Then, the IFFT for each sub-block is separately performed and then weighted by a corresponding complex phase factor [14]. The early proposed PTS methods involved the transmission of SI for recovery of information. However, a study in [11], proposed a method to eliminate the transmission of SI. The proposed method embeds SI into the rotating phase vectors shifted by a known offset. However, this method has intensive computation and this leads to its inefficiency. Another method is Frequency-Selective PAPR Reduction method for OFDM which is proposed in [18]. In this scheme, an efficient and more flexible PAPR reduction solution known as Iterative Clipping and Error Filtering (ICEF) was envisaged. This method allows for control of noise resulted from clipping process. Different from the earlier ICF method, the new proposed ICEF method is basically based on explicitly separating the clipping noise in frequency domain, within the overall iterative procedure and adopting a frequency domain mask to control the noise power [18]. In this scheme, a subset of sub carriers marked active ($N_{active} < N$) are used and in turn, this reduces the spectral efficiency of OFDM.

TABLE I. Comparison of PAPR Reduction Techniques in OFDM System

Reduction Technique	Name of Parameters		
	Signal Distortion	Power Increase	Data rate Reduction
Clipping and Filtering	Yes	No	No
Coding	No	No	Yes
Partial Transmit Sequence (PTS)	No	No	Yes
Selective Mapping (SLM)	No	No	Yes
Interleaving	No	No	Yes
Tone Reservation (TR)	No	Yes	Yes
Tone Injection	No	Yes	No

Also, a Peak-to-Average Power Ratio Reduction Using New Swarm intelligence algorithm in OFDM system was earmarked in [19]. In this algorithm, the PTS scheme is optimized in terms of phase search and SI is transmitted for to be used for data recovery at the receiver. This method suffers the same issue of SI transmission as the former PTS although, the algorithm is less complex and converges fast as compared to that of normal PTS. Musabe *et al*. [19] proposed another new PAPR reduction method based on advanced peak windowing and clipping techniques [20]. Also a New Nonlinear Companding Algorithm Based on Tangent Linearization Processing for PAPR Reduction in OFDM Systems was proposed in Ref. [21]. Each of the proposed technique in the literate has its advantages and disadvantages and using any of the technique, PAPR will be reduced at certain level. A comparative study of different PAPR reduction techniques based on signal distortion, power increase and data rate loss was done in [22] and the results is as shown in Table I.

Among of the above-mentioned methods for PAPR reduction, SLM and PTS are widely used methods [23]. Traditional SLM algorithm is a better performance algorithm in probability technology, and it is an algorithm for reducing PAPR without distortion [24]. In this paper, a combination of Selective Mapping (SLM) and Hadamard Transformation is presented.

III. An Overview of OFDM

Orthogonal Frequency Division Multiplexing (OFDM) is a multicarrier modulation in which a single large stream of data is subdivided and transmitted using several narrowband overlapping subcarriers which are orthogonally closely spaced as illustrated in figure 1. The bandwidth of the subcarriers is small compared with the coherence bandwidth of the channel and therefore the individual subcarrier experience flat fading which allows for simple equalization. This technique offers high spectral efficiency and is robust against multipath and Doppler effects. The high data rate stream in OFDM system is split into several equally spaced lower data rate stream which are then transmitted simultaneously over a larger number of sub carriers [25]. OFDM is a very attractive technique for wireless Communications [26]. Due to its numerous advantages, it offers, OFDM has drawn major attention to researchers in the area of broadband wireless communication. In order to obtain an OFDM symbol for transmission, data inputs are passed through some signal conditionings like source and channel coding and interleaving in order to obtain robust signal against channel impairments. Various multicarrier modulation schemes like QAM, PSK among others are used to modulate each subcarrier at low symbol rates. The modulated symbols are then converted from serial to parallel and fed into the inverse discrete Fourier transform which is done using IFFT. Afterward, a cyclic prefix is added to produce an OFDM symbol as illustrated in the block diagram in Figs. 1–2.

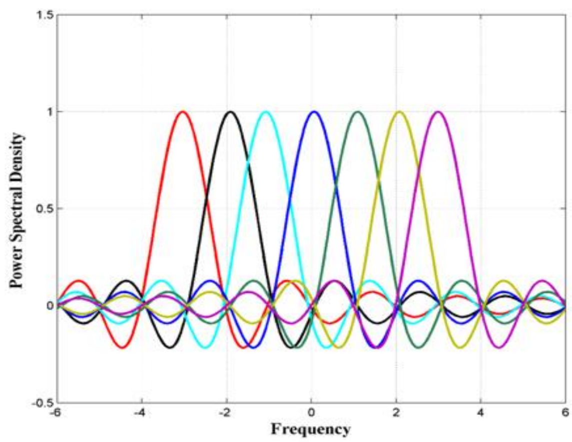

Fig. 1. Subcarriers arrangement in OFDM systems.

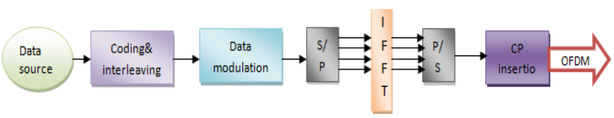

Fig. 2. OFDM symbol generation at the transmitter side.

For N–subcarriers, an OFDM symbol s(t) generation is given by the Eq. (1):

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi nk/N} \quad (1)$$

where x_n is the nth sample of an OFDM symbol in time domain, X_k $(0 \le k \le N-1)$ are statistically independent signals modulated by Quadrature amplitude modulation (QAM) scheme on different subcarriers in frequency domain and N is the total number of subcarriers [27]. OFDM *Symbol duration* (T_s) is given by Eq. (2).

$$T_s = T_u + T_g \quad (2)$$

where T_u is the useful symbol duration and T_g is the guard band duration (cyclic prefix duration).

IV. PAPR in OFDM Systems

Peak to Average Power Ratio (PAPR) is the ratio of maximum power to average power of samples in an OFDM symbol. The peak amplitude and hence the peak power in the output is resulted when different modulated sub-channels align up coherently [28, 29]. When the IFFT sum in time domain is performed, it may result into high peak amplitude relative to average amplitude of all symbols. This leads to a very high value of PAPR resulting in distortions of the output signal when passing through High Power Amplifier (HPA) [23]. HPA operates more efficient and smoother in its linear region and this minimizes signal distortion, out-of-band noise and BER degradation. A large Peak-to-Average Power Ratio (PAPR) can cause the Power Amplifiers (PAs) to operate in the nonlinear regime, and therefore lead to signal distortion and data rate degradation[30]. Besides that, high PAPR needs Digital to Analogue Converter (DAC) with high resolution to contain the maximum amplitude level and this may lead to inefficiency operation of DAC too.

Mathematically, PAPR of OFDM signal is determined by the ratio between the peak power and its average power as given in Eq. (5). A sample of OFDM symbol in time domain is given in Eq. (3) and average power of samples is given in Eq. (4).

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} X_k e^{j2\pi nkft}$$

$$, n = 0, 1, 2, .., N-1 \quad (3)$$

From Eq. (3), the average power of OFDM sample is calculated using Eq. (4).

$$E(|x_n|^2) = \frac{1}{N} \sum_{k=0}^{N-1} \left| X_k e^{j2\pi fkt} \right|^2 \quad (4)$$

Peak to average power in Eq. (5) is given as the ratio of maximum power to average power Eq. (4) of OFDM samples.

$$PAPR = 10 \log \left[\frac{max|s(t)|^2}{E|s(t)|^2} \right] \quad (5)$$

where x_n are Time domain symbols

X_k are Frequency domain symbols

In this article, PAPR is evaluated by Complementary Cumulative Distribution Function (CCDF) tool which is normally used to illustrate any reductions in PAPR. The CCDF of PAPR defines the probability that the PAPR of an OFDM frame exceeds a given reference value PAPRo [29, 31]. The complementary cumulative distribution function is expressed as in Eq. (6).

$$ccdf(x) = 1 - (1 - e^{-x}) \quad (6)$$

The probability distribution function for PAPR greater than a certain threshold (x) is therefore expressed as in Eq. (7).

$$P(PAPR > x) = 1 - (1 - e^{-x})^N \quad (7)$$

OFDM PAPR reduction has remained an active area of research for long time and many alternatives aimed at reducing PAPR have been proposed in the literature but each method has its own advantages and disadvantages. Different applications chooses different methods for PAPR reduction that best suit them when the benefits outweigh the drawbacks [32].

V. Proposed SLM-HT Method

In this study, we propose a combination of Hadamard Transformation and Selective Mapping (SLM-HT) Technique. Hadamard Transform matrix (H) is a standard square matrix of order N in which all elements in the matrix are 1 and –1 only. The use of Walsh Hadamard transform in PAPR reduction was proposed in the paper by Park *et al*. [32] where Hadamard transform scheme was used to reduce the occurrence of the high peaks. The reason for using Hadamard transform is to reduce the autocorrelation of input sequence in order to reduce the peak to average power problem and this does not require side information to be transmitted to the receiver [33]. By taking the number of OFDM subcarriers as the order N of Hadamard transform we can use the matrix for producing less correlated symbols. For instance, the Hadamard matrix of order 4 is as shown in Eq. (8).

$$H_4 = \frac{1}{\sqrt{4}}\begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix} \quad (8)$$

On the other hand, Selective Mapping (SLM) as discussed earlier is a promising technique for PAPR reduction in OFDM system. When combined with Hadamard Transform gives promising results in PAPR reduction. Figs. 3–4 shows how Selective Mapping (SLM) and Hadamard Transform (HT) can be combined together. The basic idea of SLM is to produce large but finite number of alternatives transmit sequences from the same data source and finally select signal which exhibits the lowest PAPR for transmission. In our proposed method, the input data streams are process as follows:

- The input data undergoes serial to parallel conversion to produce data symbol $\boldsymbol{X} = (\boldsymbol{X_0}, \boldsymbol{X_1}, \dots, \boldsymbol{X_{N-1}})$ with N data points.
- The parallel data symbol stream $\boldsymbol{X} = (\boldsymbol{X_0}, \boldsymbol{X_1}, \dots, \boldsymbol{X_{N-1}})$ are multiplied by V independent phase sequence $\boldsymbol{P} = (\boldsymbol{P_0}, \boldsymbol{P_1}, \dots, \boldsymbol{P_{N-1}})$ to produce V alternative data symbols with the same information.

$$X_{SLM} = X_n . \times P_n \;, n = 0,1, \dots, N-1$$

- The resulting V alternative symbols $X_{SLM} = (X_{slm}^0, X_{slm}^1, \dots, X_{slm}^{N-1})$ are multiplied by Hadamard transform matrix H_N. $(X_H = H_N * X_{slm}^T)$
- The N-point IFFT is then performed to all V symbols with the same information to produce time domain symbol $x_{SLM-HT} = IFFT(X_{SLM-HT})$.
- PAPR is calculated for all V sets of x_{SLM-HT}. Lastly, the PAPR of independent data blocks [34] will be compared and the candidate with the lowest evaluated PAPR will be selected for transmission.

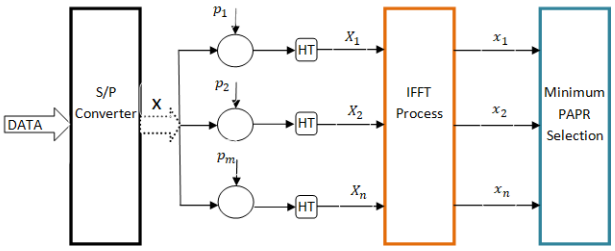

Fig. 3. Basic principle of PAPR reduction using a combination selective mapping and Hadamard transform.

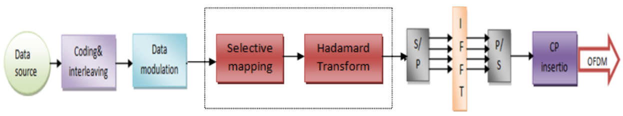

Fig. 4. Proposed block for OFDM symbol generation at the transmitter side.

VI. Results and Discussion

Since DAB system is intended for both mobile and fixed receivers, both additive white Gaussian Noise Channel (AWGN) and Rayleigh Fading channel environments were considered and evaluated. The proposed method was evaluated both in terms of PAPR reduction and BER performance using simulation parameters in Table II as discussed in part 5.1 to 5.3.

TABLE II. Simulation Parameters

S/N	Parameter	Value
1	No of subcarriers (N)	1024
2	Modulation	QAM
3	QAM Level (M)	4,16 and 64
4	Data symbols	10240
5	Guard interval	10% of N

A. *Results on PAPR Reduction*

The proposed method involves the use of Selective Mapping and Hadamard transform methods. Selective mapping technique was chosen because is widely used technique in OFDM systems to reduce PAPR as it has less signal distortion. Also, Hadamard Transform was chosen due to its ability to reduce autocorrelation between symbols which is the desirable effect upon reducing PAPR among symbols. The analysis of the proposed technique was done using Complementary Cumulative Distribution Function (CCDF) in Eq. (7). The results in PAPR reduction performance of the proposed SLM-HT method were compared with the other techniques as shown in Figs. 5–7 using 16 using different QAM levels.

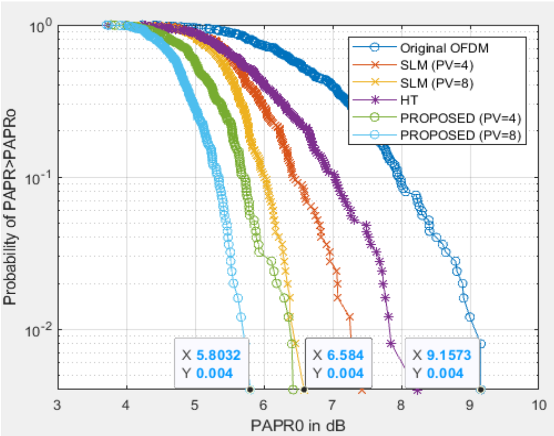

Fig. 5. CCDF results of PAPR with different algorithms using 4-QAM and 64 subcarriers.

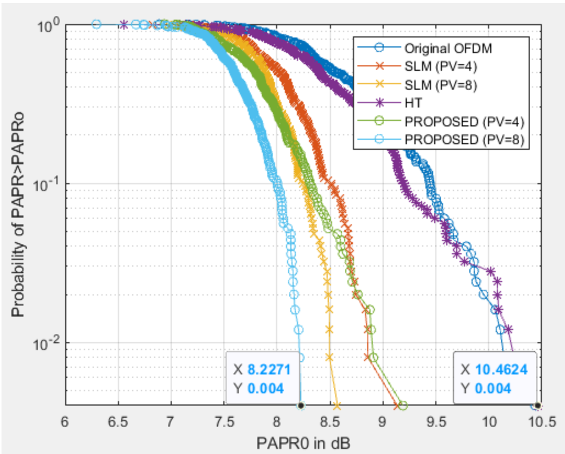

Fig. 6. CCDF results of PAPR with different algorithms using 16-QAM and 1024 subcarriers.

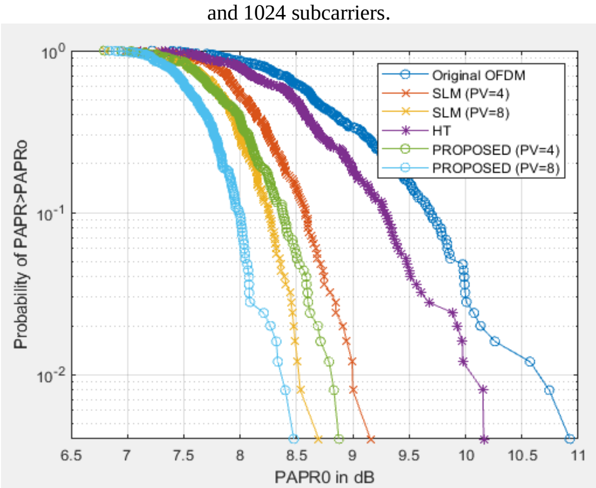

Fig. 7. CCDF results of PAPR with different algorithms using 64-QAM and 1024 subcarriers.

From Fig. 5 for instance, it can be seen that the proposed scheme (SLM-HT) achieves a PAPR reduction of 5.84dB. This is an improvement of 4.26dB from that of the original OFDM. The achievable peak to average power ratio results at the probability of 0.004 from different reduction methods using 4-QAM and 64 subcarriers are summarized in the Table III.

TABLE III. ACHIEVABLE PAPR AT THE PROBABILITY OF 0.004

S/N	Reduction Method	Achievable PAPR (dB)	Improvement (dB)
1	Original	10.10	0
2	HT	8.05	2.05
2	SLM (pv=4)	7.18	2.92
3	SLM (pv=8)	6.55	3.55
4	Proposed (pv=4)	6.40	3.70
5	Proposed (pv=8)	5.84	4.26

B. BER Performance in AWGN and Rayleigh Fading Channel

The study went further onto comparing the BER of the proposed (SLM-HT) PAPR reduction method against the original OFDM in additive white Gaussian noise (AWGN) and Rayleigh channel. BER performance was plotted by varying the channel Signal to Noise Ratio (SNR) from 10dB to 20dB against Bits Error Rates. Figs 8–10 present the results of BER against SNR in an Additive White Gaussian Noise (AWGN) channel. From these figures it can be observed that there is no significant degradation in BER of our proposed scheme when compared to that of original OFDM. Figs. 9–11 presents the results of BER against SNR in a channel which combine both AWGN and Rayleigh fading effects. The result shows an expected improvement of BER of our proposed scheme as compared to that of the original OFDM.

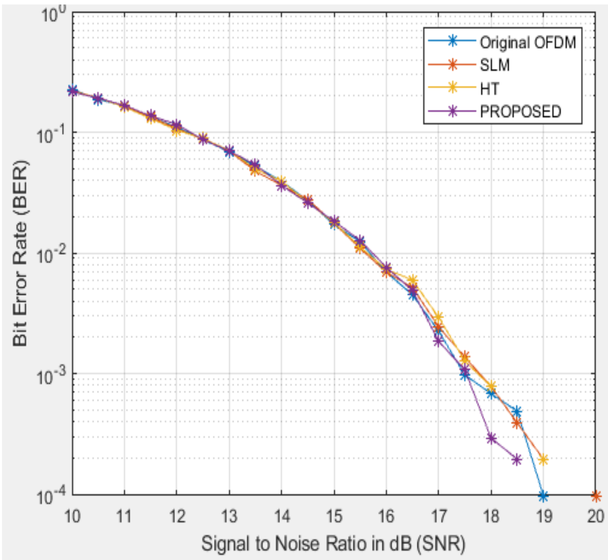

Fig. 8. BER performance of OFDM symbols using 16-QAM in AWGN channel.

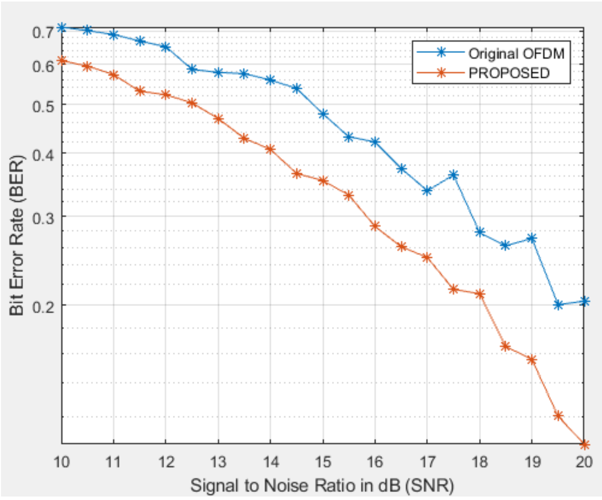

Fig. 9. BER Performance of OFDM symbols using 16-QAM in both AWGN and Rayleigh fading channel.

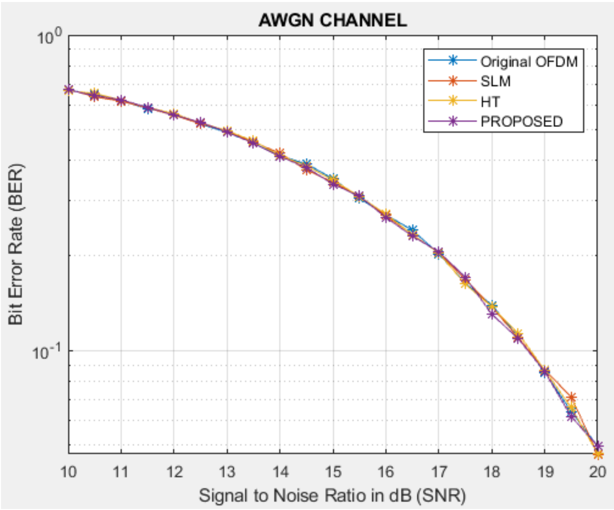

Fig. 10. BER performance of OFDM symbols using 64-QAM in AWGN channel.

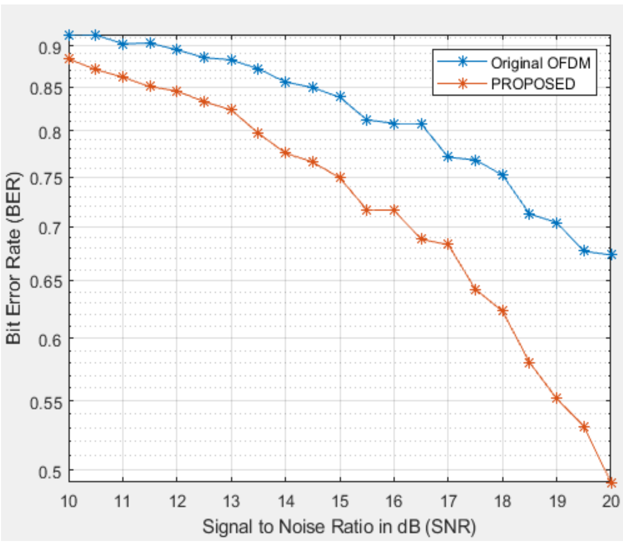

Fig. 11. BER performance of OFDM symbols using 64-QAM in both AWGN and Rayleigh fading channel.

C. Comparison with other Techniques

Table IV shows a comparison of the proposed PAPR reduction technique with other available methods. The comparison was done by looking on whether or not the techniques introduce costs in the areas of signal distortion, power utilization, BER, complexity and data rate loss.

TABLE IV. COMPARISON OF THE PROPOSED AND OTHER DIFFERENT PAPR REDUCTION TECHNIQUES IN OFDM

Reduction Technique	**Name of Parameters**			
	Signal Distortion	**BER Increase**	**Tx and Rx Complexity**	**Data rate loss**
Clipping and Filtering	Yes	Yes	No	No
Partial Transmit Sequence (PTS)	No	No	Yes	No
Selective Mapping (SLM)	No	No	Yes	No
Proposed Scheme	No	No	Yes	No

The proposed PAPR reduction method which combines a SLM with Hadamard transform is expected to have added complexity at both transmitter and receiver sides as compared to SLM. This is due to the added computations of Hadamard matrices at both transmitter and receiver sides. In spite that the proposed technique gives better reduction of PAPR, its performance price is reflected on the increased execution time as shown in Table V. However, these values may change depending on the computation speed of the machine (Transmitter and Receiver) used.

TABLE V. EXECUTION TIME OF DIFFERENT PAPR REDUCTION TECHNIQUES

Reduction Technique	**Execution Time (Seconds)**
Selective Mapping (SLM)	0.001045
Hadamard Transform (HT)	0.215717
Proposed SLM with HT	0.217067

VII. CONCLUSION

In this paper a combination of Selective Mapping and Hadamard Transformation (SLM-HT) scheme is presented and examined for performance in terms of PAPR reduction and bits error rates. The proposed scheme was evaluated using MATLAB software employing 4, 16 and 64QAM symbol mapping which is used in DAB systems. The plot of complementary cumulative distribution function against peak to average power ratio and BER against SNR of each method was done as presented in the results discussion section. From the results, it can be seen that, the proposed scheme gives an improved results in terms of PAPR reduction and BER. However, further study is recommended to reduce the execution time of the proposed scheme.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of Interest

The authors declare that they have no conflicts of interest.

Author Contributions

Joseph Sospeter did the model preparation, wrote all the MATLAB codes and simulation. Elijah Mwangi advised on the model parameters, newness of the references and checked the format and English grammar of the paper. Nerey Mvungi also advised of the efficiency of the model, checked English grammar, he also participated in making sure that the latest paper was submitted on time; All authors had approved the final version.

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References

[1] K. Zyka, "The digital audio broadcasting journey from the lab to listeners – The Czech Republic case study," *Radioengineering*, vol. 27, no. 2, pp. 483–490, 2019. doi: 10.13164/RE.2019.0483

[2] T. L. W. Hoeg, *Digital Audio Broadcasting Principles and Applications of DAB, DAB+ and DMB*, 3rd ed., John Wiley & Sons, 2009.

[3] A. Joshi, S. Saxena, and S. Jain, "PAPR reduction in OFDM system using hybrid PTS-RCMN scheme," *Int. J. Wirel. Mob. Comput.*, vol. 13, no. 1, pp. 15–22, 2017. doi: 10.1504/IJWMC.2017.087352

[4] P. Gupta, H. P. Thethi, and A. Tomer, "An efficient and improved PTS algorithm for PAPR reduction in OFDM system," *Int. J. Electron.*, vol. 109, no. 7, pp. 1252–1277, 2022. doi: 10.1080/00207217.2021.1966671

[5] K. Liu and Y. Liu, "Adjustable nonlinear companding transform based on scaling of probability density function for PAPR reduction in OFDM systems," *IEEE Trans. Broadcast.*, vol. 67, no. 2, pp. 524–537, 2021. doi: 10.1109/TBC.2021.3051520

[6] S. Prasad and S. Arun, "Performance analysis of different matrices-based SLM techniques for reducing PAPR in OFDM systems," in *Proc.Computational Methods and Data Engineering*, 2023, pp. 359–377.

[7] K. Anoh, C. Tanriover, and B. Adebisi, "On the optimization of Iterative clipping and filtering for PAPR reduction in OFDM systems," *IEEE Access*, vol. 5, no. c, pp. 12004–12013, 2017. doi: 10.1109/ACCESS.2017.2711533

[8] M. Ali, R. K. Rao, and V. Parsa, "PAPR reduction in OFDM systems using clipping based on symbol statistics," *Can. Conf. Electr. Comput. Eng.*, vol. 1, no. 2, pp. 2–6, 2017. doi: 10.1109/CCECE.2017.7946742

[9] K. H. Kim, "On the shift value set of cyclic shifted sequences for PAPR reduction in OFDM systems," *IEEE Trans. Broadcast.*, vol. 62, no. 2, pp. 496–500, 2016. doi: 10.1109/TBC.2016.2529292

[10] J. Zheng and H. Lv, "Peak-to-average power ratio reduction in OFDM index modulation through convex programming," *IEEE Commun. Lett.*, vol. 21, no. 7, pp. 1505–1508, 2017. doi: 10.1109/LCOMM.2017.2690418

[11] H. Joo, K. Kim, J. No, and D. Shin, "New PTS schemes for PAPR reduction of OFDM signals without side information," *IEEE Transactions on Broadcasting*, pp. 1–9, 2017.

[12] S. Y. Zhang and B. Shahrrava, "A SLM scheme for PAPR reductionin polar coded OFDM-IM systems without using side information," *IEEE Trans. Broadcast.*, vol. 67, no. 2, pp. 463–472, 2021. doi: 10.1109/TBC.2020.3039696

[13] V.N. Tran, "Hybrid scheme using modified tone reservation and clipping-and-filtering methods for peak-to-average power ratio reduction of OFDM signals," *Signal Processing*,vol. 158, 2019.

[14] S. Gokceli, T. Levanen, T. Riihonen, M. Renfors, and M. Valkama, "Frequency-selective papr reduction for OFDM," *IEEE Trans. Veh. Technol.*, vol. 68, no. 6, pp. 6167–6171, 2019. doi: 10.1109/TVT.2019.2909643

[15] E. Abdullah, A. Idris, and A. Saparon, "Papr reduction using scs-slm technique in stfbc mimo-ofdm," *ARPN J. Eng. Appl. Sci.*, vol. 12, no. 10, pp. 3218–3221, 2017.

[16] M. H. Aghdam and A. A. Sharifi, "PAPR reduction in OFDM systems: An efficient PTS approach based on particle swarm optimization," *ICT Express*, vol. 5, no. 3, pp. 178–181, 2019. doi: 10.1016/j.icte.2018.10.003

[17] S. Sengar and P. P. Bhattacharya, "Performance improvement in OFDM system by PAPR Reduction," *Signal Image Process. Int. J.*, vol. 3, 2012.

[18] A. Lahcen, A. Kamal, H. Mustapha, E. Ali, A. Saida, and A. Adel, "Peak-to-average power ratio reduction using new swarm intelligence algorithm in OFDMsystems," *Procedia Manuf.*, vol. 32, pp. 831–839, 2019. doi: 10.1016/j.promfg.2019.02.291

[19] R. Musabe, M. B. Lionel, V. Mugongo Ushindi, M. Atupenda, J. Ntaganda, and G. Bajpai, "PAPR reduction in LTE network using both peak windowing and clipping techniques," *J. Electr. Syst. Inf. Technol.*, vol. 6, no. 1, pp. 1–11, 2019. doi: 10.1186/s43067-019-0004-1

[20] H. A. Reza Sayyari, Jafar Pourrostam, "Efficient PAPR reduction scheme for OFDMNOMA systems based on DSI and precoding methods," *Phys. Commun.*, vol. 47, 2021.

[21] K. Liu, L. Wang, and Y. Liu, "A new nonlinear companding algorithm based on tangent linearization processing for PAPR reduction in OFDM systems," *China Commun.*, vol. 17, no. 8, pp. 133–146, 2020. doi: 10.23919/JCC.2020.08.011

[22] A. Chougule, S. Manjare, and R. Anande, "Comparative study of papr reduction techniques in ofdm," *Int. J. Adv. Eng. Res. Dev.*, vol. 4, no. 3, pp. 5515–5521, 2017. doi: 10.21090/ijaerd.24741

[23] M. Fidele, M. Singh, R. K. Singh, and P. Gupta, "Peak to average power ratio reduction for OFDM system using different peak windowing and modulation techniques," *Far East J. Electron. Commun.*, pp. 33–45, 2016. doi: 10.17654/ECSV3PI16033

[24] Y. Liu, Z. Tong, W. Zhang, T. Li, and M. Wang, "A hybrid algorithm for reducing PAPR of CO-OFDM system based on fast hadamard transformation cascading SLM," *Optoelectron. Lett.*, vol. 17, no. 9, pp. 534–538, 2021. doi: 10.1007/s11801-021-0194-3

[25] M. S. K. Muralibabu, "PAPR performance improvement in OFDM system using DCT based on adjacent symbol grouping," *Appl. Mech. Mater.*, 2014.

[26] A. S. Parihar and S. Singh, "PAPR Reduction Technique in OFDM: A Review," *IJMRS's Int. J. Eng.*, vol. 3, no. 2, 2014.

[27] M. Y. A. Jawhar, L. Audah, N. S. M. A. Taher, K. N. Ramli, and M. S. Shah, and M. Musa, "A review of partial transmit Sequence for PAPR reduction in the OFDM systems," *IEEE Access*, pp. 18021–18041, 2019.

[28] T. G. G. Lema and D. H. H. B. Reda, "LTE quality of service enhancement under OFDM modulation techniques," *Wirel. Pers. Commun.*, vol. 113, pp. 995–1008, 2020.

[29] A. A. Abdulkafi, M. Y. Alias, and Y. S. Hussein, "A novel approach for PAPR reduction in OFDM-based visible light communications," in *Proc.2017 Int. Conf. Platf. Technol. Serv. PlatCon*, pp. 1–4, 2017. doi: 10.1109/PlatCon.2017.7883678

[30] M.-T. Nguyen, G. Kaddoum, B. Selim, K. V Srinivas, and P. F. de A. Filho, "Deep unfolding network for PAPR reduction in multicarrier OFDM systems," *IEEE Commun. Lett.*, vol. 26, no. 11, pp. 2616–2620, 2022. doi: 10.1109/LCOMM.2022.3195042

[31] S. Kiambi, E. Mwangi, and G. Kamucha, "Effect of OFDM signal structure and subcarrier modulation on the reduction of the signal peak power," in *Proc.2017 IEEE AFRICON Sci. Technol. Innov. Africa*, pp. 262–266, 2017. doi: 10.1109/AFRCON.2017.8095492

[32] D. H. C. K. M. Park, H. Y. Jun, J. Cho, and N. Cho, "PAPR reduction in OFDM transmission using Hadamard transform," in *Proc.2000 IEEE Int.* Conf. *Commun. ICC 2000. Glob. Converg. Through Commun.*, vol. 1, pp. 430–433, 2000.

[33] Z. Wang, "Reduction of PAPR of OFDM signals by combining PTS with Hadamard transform," in *Proc.Fourth International Conference on Machine Vision (ICMV 2011) Computer Vision and Image Analysis Pattern Recognition and Basic Technologies*, 2011.

[34] V. G. S. S. M. Krishna and B. Somasekhar, "A study on PAPR reduction and channel estimation in MIMO-OFDM system using wavelet transform," in *Proc.International Conference on Energy, Communication, Data Analytics and Soft Computing (ICECDS)*, p. 3, 2017.