PAPR Reduction in OFDM System with $\pi/4$-QPSK Mapper Using Improved PTS Technique

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Abstract—An Orthogonal Frequency Division Multiplexing (OFDM) system with $\pi/4$-QPSK (Quadrature Phase Shift Keying) mapper is considered. Partial Transmit Sequence (PTS) technique with an improved partitioning technique is proposed for PAPR reduction. Even though in PTS, the pseudo-random partitioning method yields the best PAPR reduction compared to adjacent and interleaved partitioning methods, there is a lack of structure in partitioning and hence increases system complexity both in the transmitter and the receiver. The proposed scheme offers a systematic and simple construction of adjacently partitioned sub-blocks using the Magic squares to pseudo-randomize them. Numerical results show that the proposed method outperforms both the adjacent and the interleaved partitioning methods and has nearly the same performance as that of pseudo-random partitioning method.

Index Terms—Orthogonal Frequency Division Multiplexing (OFDM), Peak to Average Power Ratio (PAPR), Partial Transmit Sequence (PTS), Partitioning, Adjacent, Interleaved, Pseudo-random.

I. Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is widely employed in wireless and wired communication applications such as Digital Video Broadcasting (DVB) and 3GPP Long Term Evolution (LTE) [1]. Also, OFDM is the base technology for Power Line Communication (PLC) system standard for smart grid applications such as IEEE 1901.2, PoweRline Intelligent Metering Evolution (PRIME), G3-PLC, and HomePlug Green PHY [2]. Parallel narrowband subcarrier transmission is achieved by an OFDM system, thus, high data rates are attained. As a result, OFDM system can alleviate the effects of multipath channel. However, OFDM system exhibits large amplitude variations attributable to the IFFT operation that results in high peak-to-average power ratio (PAPR). Therefore, when OFDM signal traverses the High Power Amplifier (HPA) block at the transmitter, it is affected by significant nonlinear distortion. Subsequently, both Out-of-Band (OOB) noise and In-Band (IB) noise are developed, resulting in spectral spreading and Inter-carrier Interference (ICI) [1].

Several techniques have been proposed to lessen the effect of high PAPR in OFDM systems. These techniques are classified into three categories: i) signal distortion techniques, such as clipping, windowing, and companding transforms; ii) distortionless signal techniques such as Selective Mapping (SLM), Partial Transmit Sequence (PTS), and Tone Injection (TI). iii) coding techniques such as Linear Block Coding (LBC), cyclic coding, and Golay Complementary Sequences (GCS) [3]. Among these, PTS is an attractive technique, as it provides considerable PAPR reduction. However, this method requires side information to be conveyed to the receiver.

The PAPR reduction using PTS is dependent on the chosen phase sequence candidates, the number of sub-blocks V, and the type of sub-block partitioning [4]. In [5], an analysis of PTS with three sub-block partitioning namely, adjacent, interleaved, and pseudo-random, is presented. In [6] it is shown that pseudo-random partition attains the best performance. As it has better autocorrelation properties compared to adjacent and interleaved partitioning. In [7], it is noted that the more the independent the better is the PAPR reduction. However, a systematic pseudo-random sub-block partitioning alleviates the system implementation complexity [5]. Hence, it is important to design a partitioning scheme that has the structural simplicity of either adjacent or interleaved partitioning and in the same time achieves the PAPR reduction capability of pseudo-random partitioning technique.

In this paper, PAPR performance of OFDM system with $\pi/4$-QPSK mapper using PTS with adjacent, interleaved, and pseudo-random partitioning is considered. A new partitioning scheme is proposed that achieves better PAPR reduction than adjacent and interleaved methods, and has same performance as that of pseudo-random method. The simulation results are presented for OFDM system with 64- and 128-subcarriers.

This paper is organized as follows: Section II presents the system model. Section III describes the proposed partitioning scheme. Section IV presents the simulation results, and the paper is concluded in Section V.

II. OFDM System Model with PTS Technique

A. $\pi/4$-QPSK Mapper

In the OFDM system, $\pi/4$-QPSK data mapper is used and its constellation is formed by switching between two QPSK constellations [8]. The output of $\pi/4$-QPSK mapper $\in \{\pm 1, \pm j, \pm 0.7071 \pm 0.7071j\}$. The $\pi/4$-QPSK

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mapper limits the maximum phase change to 135°, rather than 180° for QPSK [8]. In addition, it is well-known that $\pi/4$-QPSK performs better than QPSK in the presence of multipath spread and fading [9].

B. OFDM Signal and PAPR Definition

An OFDM signal is the sum of many independent signals modulated onto subcarriers of equal bandwidth. The complex baseband representation of such a signal containing N subcarriers can be written as:

$$D(t) = \frac{1}{N}\sum_{k=0}^{N-1} C_k\, e^{j2\pi f_k t}, \qquad 0 \le t \le T_s \qquad (1)$$

where $j = \sqrt{-1}$, T_s is the OFDM symbol duration, $[C_0, C_1, \dots, C_{N-1}]$ is a length-N complex data block, and $f_k = k/T_s$, $k = 0, 1, \dots, N-1$, are the N subcarrier frequencies. For a $\pi/4$ -QPSK mapper $C_k \in \{\pm 1, \pm j, \pm 0.7071 \pm 0.7071j\}$. It is noted that $T_s = 2T_b N$, where, T_b is the bit duration. When the OFDM signal in (1) is sampled at $t = n2T_b$, we obtai

$$D_n = D(n2T_b) = \frac{1}{N}\sum_{k=0}^{N-1} C_k\, e^{\frac{j\pi nk}{N}}, n = 0, 1, \dots N-1 \quad (2)$$

The PAPR of the OFDM signal in (1) is given by:

$$PAPR = \frac{\underset{0 \le t \le T_s}{max} |D(t)|^2}{\frac{1}{T_s}\int_0^{T_s} |D(t)|^2\, dt}, \qquad (3)$$

An equivalent of (3) using discrete complex baseband signal is given by (2):

$$PAPR = \frac{max\{|D_n|^2, n = 0, 1, \dots, LN-1\}}{\frac{1}{LN}\sum_{n=0}^{LN-1} |D_n|^2}, \qquad (4)$$

where L is the oversampling factor and typically $L \ge 4$ approximates (3).

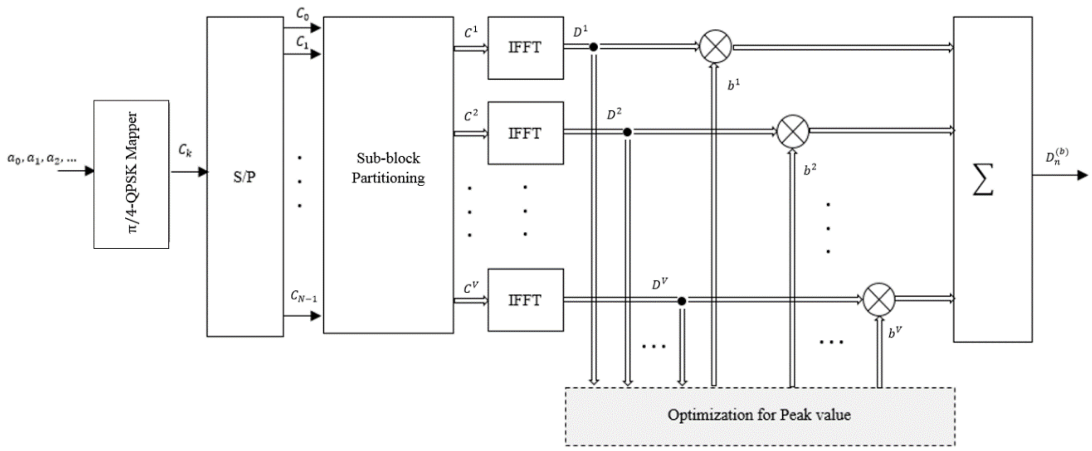


Fig. 1. Partial block diagram of OFDM system with $\pi/4$-QPSK mapper and PTS technique.

C. Partial Transmit Sequence Technique

Fig. 1 shows the block diagram of PTS technique used in an OFDM system. The data vector $C = [C_0, C_1, \dots, C_{N-1}]$ is partitioned into V disjoint vectors or sub-blocks, known as the partial transmit sequences, given by:

$$C^v = [C_0^v, C_1^v, \dots, C_{N-1}^v] \quad , v = 1,2, \dots, V \qquad (5)$$

It is noted that each sub-block contains $P = N/V$ number of data symbols of vector C such that,

$$C = \sum_{v=1}^{V} C^v \qquad (6)$$

For example, there are $P = 2$ data symbols when $N = 8$ and $V = 4$. The manner in which P elements are chosen from data vector C gives rise to the type of partitioning such as adjacent, interleaved, and pseudo-random partitioning. Once partitioned sub-blocks are defined, V phase sequences b^v, $v = 1,2, \dots, V$, are determined by letting $b^v = e^{j\emptyset_v}$ and $0 \le \emptyset_v \le 2\pi$. The values of $\emptyset_v$ are chosen from the set $\{\frac{2\pi l}{W}, l = 0, 1, \dots, W-1\}$ where W is the number of the permitted values of $\emptyset_v$. For example, when $W = 4$, the set of possible phases $e^{j\emptyset_v}$ is $\{+1, +j, -1, -j\}$.

The phase b^v is then multiplied with corresponding partitioned sub-vectors $C^v, v = 1, 2, \dots V$ to obtain the modified data block $C^{(b)}$ and is given by:

$$C^{(b)} = \sum_{v=1}^{V} b^v C^v \qquad (7)$$

By denoting $(b) = (b^1, b^2, \dots, b^v)$, it is noted that (b) can take values $1,2, \dots, W^V$. For example, when $W = 4$ and $V = 4$, then there are 256 possible phase sequences $(b^1, b^2, \dots, b^4)$ with $b^i \in \{+1, +j, -1, -j\}, i = 1, 2, 3, 4$.

Using the linear property of IFFT, it is noted that:

$$D = IFFT\{C\} = \sum_{v=1}^{V} IFFT\{C^v\} = \sum_{v=1}^{V} D^v \qquad (8)$$

where, $D = [D_0, D_1, \dots, D_{N-1}]$ and $D^v = [D_0^v, D_1^v, \dots, D_{N-1}^v]$, $v = 1,2,\dots,V$.

Using (7), the phase weighted $D^{(b)}$ is thus given by:

$$D^{(b)} = \sum_{v=1}^{V} b^v D^v \tag{9}$$

The objective of PTS technique is to find:

$$\min_{(b)} \left(\frac{max\{|D^{(b)}|^2, n = 0, 1, \dots, LN-1\}}{\frac{1}{LN}\sum_{n=0}^{LN-1}|D^{(b)}|^2} \right) \tag{10}$$

D. Sub-block Partitioning

The three well-known partitioning methods [5] are expl-ained next.

In adjacent sub-block partitioning, the symbol elements from vector $C = [C_0, C_1, \dots, C_{N-1}]$ chosen for the sub-block C^v is from the set $\{C_{(v-1)P}, C_{(v-1)P+1}, \dots, C_{vP-1}\}, v = 1, 2, \dots, V$. For example, with $N = 8$ and $V = 4$, there are $P = 2$ symbol elements in each sub-block partition. They are $\{C_0, C_1\}$, $\{C_2, C_3\}$, $\{C_4, C_5\}$, $\{C_6, C_7\}$ for $v = 1, 2, 3, 4$, respectively. Consequently, the partitioned sub-blocks are:

$$C^1 = [C_0, C_1, 0, 0, 0, 0, 0, 0]$$

$$C^2 = [0, 0, C_2, C_3, 0, 0, 0, 0]$$

$$C^3 = [0, 0, 0, 0, C_4, C_5, 0, 0]$$

$$C^4 = [0, 0, 0, 0, 0, 0, C_6, C_7]$$

In the case of interleaved sub-block partitioning, the symbol elements from C chosen for C^v is from the set $\{C_{(v-1)}, C_{V+(v-1)}, \dots, C_{(P-1)V+(v-1)}\}$, $v = 1, 2, \dots, V$, where $P = N/V$. Again, for $N = 8$ and $V = 4$, there are $P = 2$ symbol elements in each sub-block partition. They are $\{C_0, C_4\}, \{C_1, C_5\}, \{C_2, C_6\}, \{C_3, C_7\}$ for $v = 1, 2, 3, 4$, respecti-vely. The partitioned sub-blocks are:

$$C^1 = [C_0, 0, 0, 0, C_4, 0, 0, 0]$$

$$C^2 = [0, C_1, 0, 0, 0, C_5, 0, 0]$$

$$C^3 = [0, 0, C_2, 0, 0, 0, C_6, 0]$$

$$C^4 = [0, 0, 0, C_3, 0, 0, 0, C_7]$$

In pseudo-random sub-block partitioning $P = N/V$ elements from C are chosen randomly. One possible realization for the example of $N = 8$ and $V = 4$ is:

$$C^1 = [C_0, 0, 0, 0, 0, 0, C_6, 0]$$

$$C^2 = [0, 0, 0, 0, 0, C_5, 0, C_7]$$

$$C^3 = [0, 0, C_2, C_3, 0, 0, 0, 0]$$

$$C^4 = [0, C_1, 0, 0, C_4, 0, 0, 0]$$

III. Proposed Partitioning Scheme

A Magic square pattern is used to pseudo-randomize the partitioned sub-blocks. Magic square patterns of 4, 8, 16, and 64, can be used in an OFDM system with number of subcarriers $N = 16, 64, 256$, and 4096, respectively. For example, a Magic square pattern of 4 produces 16 elements, from 1 to 16 as shown in Table I.

TABLE I: MAGIC SQUARE PATTERN OF 4

16	2	3	13
5	11	10	8
9	7	6	12
4	14	15	1

For an OFDM system with $N = 16$ and number of partitions $V = 4$, there are $P = 4$ symbol elements of C in each partitioned sub-block. Elements of each row of the Magic square can then be used to choose elements from C for each of the 4 partitions. That is,

$$C^1 = [0, C_1, C_2, 0, 0, 0, 0, 0, 0, 0, 0, 0, C_{12}, 0, 0, C_{15}]$$

$$C^2 = [0, 0, 0, 0, C_4, 0, 0, C_7, 0, C_9, C_{10}, 0, 0, 0, 0, 0]$$

$$C^3 = [0, 0, 0, 0, 0, C_5, C_6, 0, C_8, 0, 0, C_{11}, 0, 0, 0, 0]$$

$$C^4 = [C_0, 0, 0, C_3, 0, 0, 0, 0, 0, 0, 0, 0, 0, C_{13}, C_{14}, 0]$$

Similarly, for the case of $N = 64$ and $V = 4$, there are $P = 16$ elements in each partitioned sub-block. Thus, a Magic square pattern of 8 can be used. The first sub-block can use the first 2-rows of the pattern to obtain the partitioned sub-block. The second sub-block uses the next 2-rows from the Magic square pattern, and so on and so forth, until all the 4 partitioned sub-blocks are obtained. Table II shows the Magic square pattern of 8.

TABLE II: MAGIC SQUARE PATTERN OF 8

64	2	3	61	60	6	7	57
9	55	54	12	13	51	50	16
17	47	46	20	21	43	42	24
40	26	27	37	36	30	31	33
32	34	35	29	28	38	39	25
41	23	22	44	45	19	18	48
49	15	14	52	53	11	10	56
8	58	59	5	4	62	63	1

Thus, each sub-block has 16 elements from C and the rest of the elements are zeros as shown below.

C^1 contains the following elements from C

$\{C_2, C_3, C_6, C_7, C_9, C_{12}, C_{13}, C_{16}, C_{50}, C_{51}, C_{54}, C_{55}, C_{57}, C_{60}, C_{61}, C_{64}\}$

C^2 contains the following elements from C

$\{C_{17}, C_{20}, C_{21}, C_{24}, C_{26}, C_{27}, C_{30}, C_{31}, C_{33}, C_{36}, C_{37}, C_{40}, C_{42}, C_{43}, C_{46}, C_{47}\}$

C^3 contains the following elements from C

$\{C_{18}, C_{19}, C_{22}, C_{23}, C_{25}, C_{28}, C_{29}, C_{32}, C_{34}, C_{35}, C_{38}, C_{39}, C_{41}, C_{44}, C_{45}, C_{48}\}$

C^4 contains the following elements from C

$\{C_1, C_4, C_5, C_8, C_{10}, C_{11}, C_{14}, C_{15}, C_{49}, C_{52}, C_{53}, C_{56}, C_{58}, C_{59}, C_{62}, C_{63}\}$

It is also possible to choose the partitioned sub-blocks based on columns of Magic square pattern rather than the rows of the pattern.

However, when the number of subcarriers are 32, 128, or 512, Magic square patterns cannot be applied in a straight forward manner. For these cases, to perform partitioning, first adjacent partitioning is carried out and then each sub-block is duplicated. Magic square patterns of 4, 8, or 16 can be used to pseudo-randomize the adjacently partitioned sub-blocks.

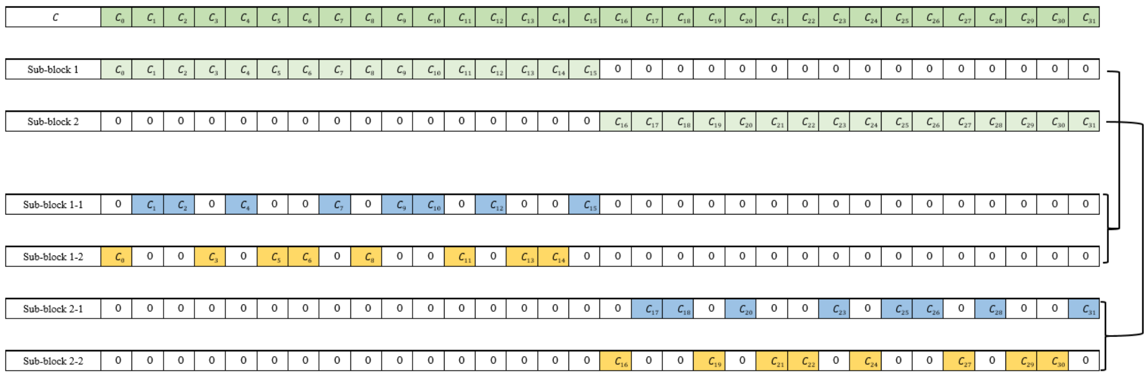


Fig. 2. Pseudo-randomized adjacent partitioning for 32-subcarriers, $V = 4$, $P = 8$, using magic square of 4.

Fig. 2 shows an example of the partitioning scheme, for 32-subcarrier OFDM system, using a Magic square pattern of 4, shown in Table I. First, the vector C is adjacently partitioned to 2 sub-blocks namely Sub-block 1 and Sub-block 2. Sub-block 1 contains elements C_0 to C_{15} of C followed by $N/2$ zeros whereas Sub-block 2 contains $N/2$ zeros followed by elements C_{16} to C_{31} of C. Next, Sub-block 1 is duplicated to obtain Sub-block 1-1 and Sub-block 1-2. By using the pattern in Table I, we can pseudo-randomize elements in sub-block 1-1 and sub-block 1-2. Therefore, the first and the second rows in Table I are chosen for sub-block 1-1 while rows three and four are used for sub-block 1-2. In the same manner, sub-block 2 will be transformed to obtain sub-block 2-1 and sub-block 2-2 which are further pseudo-randomized based on the pattern in Table I. As shown in Fig. 2. C is partitioned to obtain 4 sub-blocks and each sub-block has, $P = 8$, elements which are pseudo-randomized.

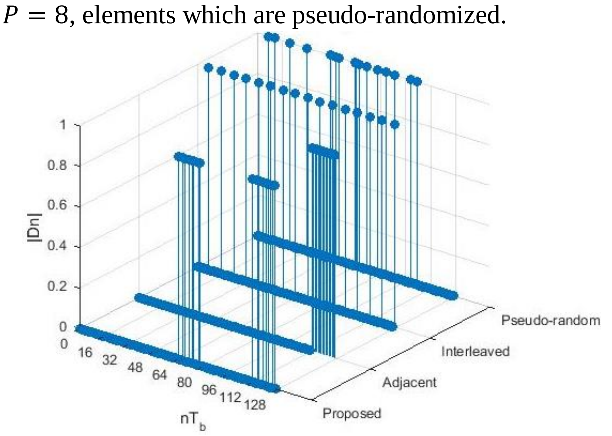


Fig. 3. Pr006Fposed, adjacent, interleaved, and pseudo-random partitions for the 8th sub-block, C^8, for a 128-subcarrier OFDM system with π/4-QPSK mapper.

Fig. 3 illustrates the proposed, and conventional partitions for sub-block C^8, for a 128-subcarrier OFDM system with $\pi/4$-QPSK mapper.

It is important to examine the correlation property of the proposed partitioning technique to ensure effectiveness of partitioning. Thus, the Periodic Autocorrelation Function (PACF) is used [6]. The periodic normalized auto-correlation function $R_{D,D}(\tau)$ of N-subcarriers D_n is given by:

$$R_{D,D}(\tau) = \frac{1}{N}\sum_{n=0}^{N-1} D_n \,.\, D^*_{n+\tau} \ mod\ N \tag{11}$$

where, D^*_n denotes the complex conjugate of D_n.

IV. Numerical Results

The PAPR performance of OFDM system with $\pi/4$-QPSK mapper in conjunction with PTS technique for the proposed, adjacent, interleaved, and random partitioning can be determined using eqn. 10. In Figs. 4(a) and 4(b), PAPR performances of 64- and 128-subcarrier systems using CCDF plots [3] are shown for two cases of $(b) = (b^1, b^2, \dots, b^v)$: i) $\tilde{b}_1 = (b^1, b^2, \dots, b^8)$ with fixed values of $b^1 = b^3 = b^5 = b^7 = +1$ and ii) $\tilde{b}_2 = (b^1, b^2, \dots, b^8)$ with fixed value of $b^1 = +1$. It is noted that $V = N/P$, which implies that in both systems, there are 8 partitions. Also, it is observed that when $\tilde{b}_1$ is used, 4 bits of side information is required to be conveyed to the receiver and when $\tilde{b}_2$ is used, 7 bits are required to be sent to the receiver. In all PAPR performance plots 100,000 OFDM symbols were considered for each plot. A summary of achievable PAPR is given in Table III. It is observed that by using $\tilde{b}_2$ a reduction of nearly $1dB$ PAPR can be achieved relative to the case when $\tilde{b}_1$ is employed; however the latter requires 3 bits fewer side information than the former to be conveyed to the receiver.

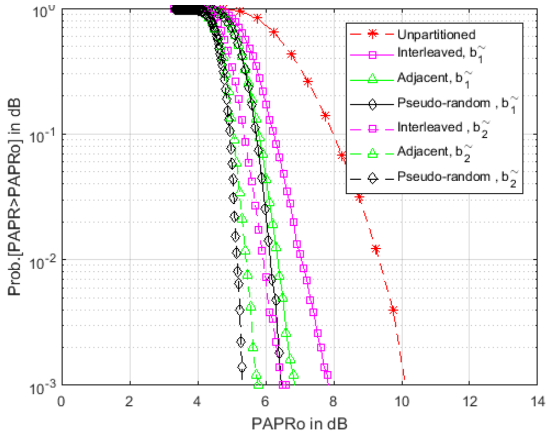


Fig. 4(a). PAPR performance of 64-subcarrier OFDM system with $\pi/4$-QPSK mapper for various partitions for, $\tilde{b}_1$, and $\tilde{b}_2$.

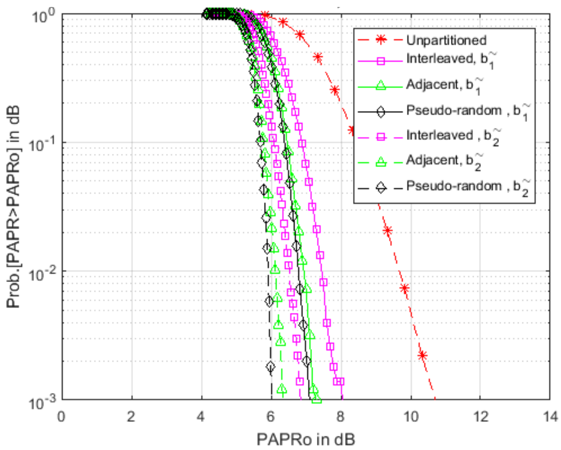


Fig. 4(b). PAPR performance of 128-subcarrier OFDM system with $\pi/4$-QPSK mapper for various partitions for, $\tilde{b}_1$, and $\tilde{b}_2$.

TABLE III: PAPR PERFORMANCE FOR 64- AND 128-SUBCARRIER OFDM SYSTEMS WITH $\pi/4$–QPSK MAPPER, FOR VARIOUS PARTITIONS

N	Partition type	Achievable PAPR in dB, $\tilde{b}_1$	Achievable PAPR in dB, $\tilde{b}_2$
64	Un-Partitioned	10.168	10.168
	Adjacent	6.751	5.782
	Interleaved	7.922	6.389
	Pseudo-random	6.513	5.293
128	Un-Partitioned	10.441	10.441
	Adjacent	7.377	6.307
	Interleaved	8.113	6.863
	Pseudo-random	7.049	6.052

In Figs 5(a) and 5(b), PAPR performances of OFDM system with $\pi/4$-QPSK mapper, are shown for 64- and 128-subcarrier for $\tilde{b}_2$, for the proposed, adjacent, interleaved, and pseudo-random partitions. It is observed that when the proposed partitioning is used, the PAPR performance is better compared to both adjacent and interleaved partitioning schemes; however, the pseudo-random partitioning achieves the best reduction in PAPR. Table IV summarizes these results.

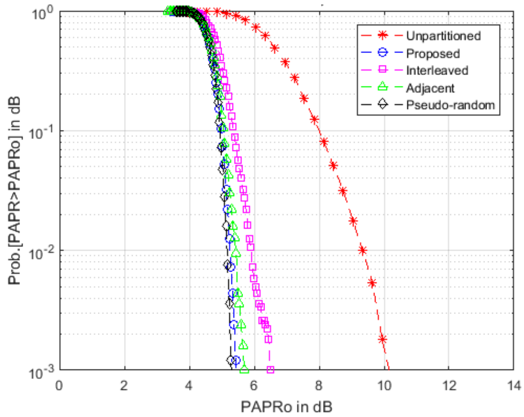


Fig. 5(a). PAPR performance of 64-subcarrier OFDM system with $\pi/4$-QPSK mapper for the proposed, adjacent, interleaved, and pseudo-random partitions, for $\tilde{b}_2$.

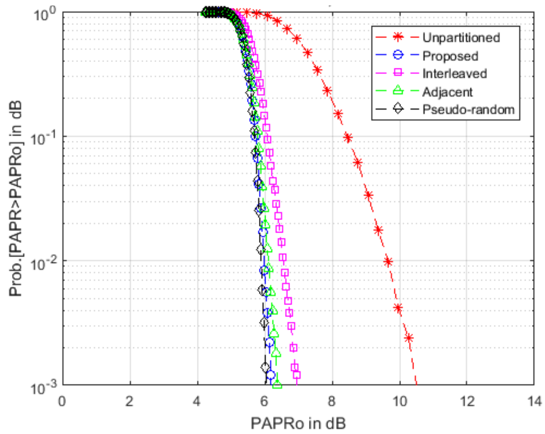


Fig. 5(b). PAPR performance of 128-subcarrier OFDM system with $\pi/4$-QPSK mapper for the proposed, adjacent, interleaved, and pseudo-random partitions, for $\tilde{b}_2$ is used.

TABLE IV: ACHIEVABLE PAPR FOR 64- AND 128-SUBCARRIER OFDM SYSTEMS WITH $\pi/4$–QPSK MAPPER

Partition type	Achievable PAPR in dB, $\boldsymbol{N = 64, \tilde{b}_2}$	Achievable PAPR in dB, $\boldsymbol{N = 128, \tilde{b}_2}$
Un-Partitioned	10.174	10.441
Proposed	5.466	6.104
Adjacent	5.871	6.307
Interleaved	6.382	6.863
Pseudo-random	5.304	6.052

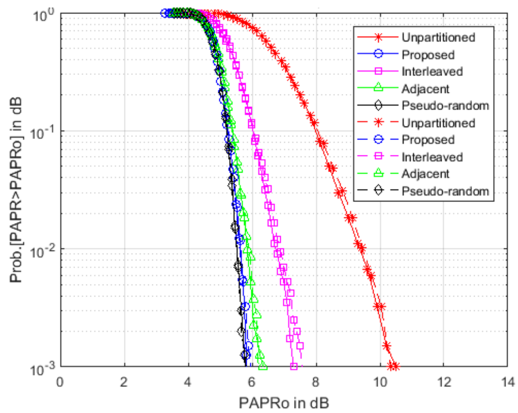


Fig. 6(a). PAPR performance comparison, for 64-subcarrier OFDM system with $\pi/4$-QPSK ($-*-$) and QPSK ($-*-$) mappers for various partitions ($V = 4$,$(b) = (b^1, b^2, b^3, b^4)$, and $b^v \in \{\pm 1, \pm j\}$).

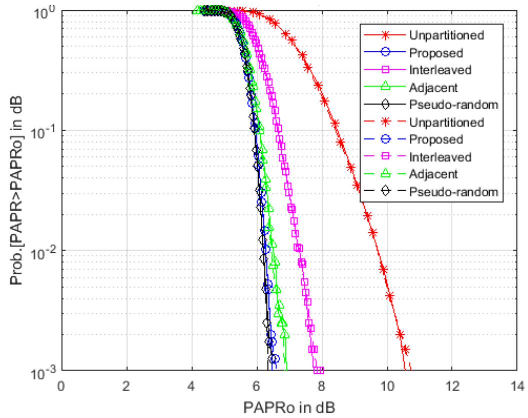
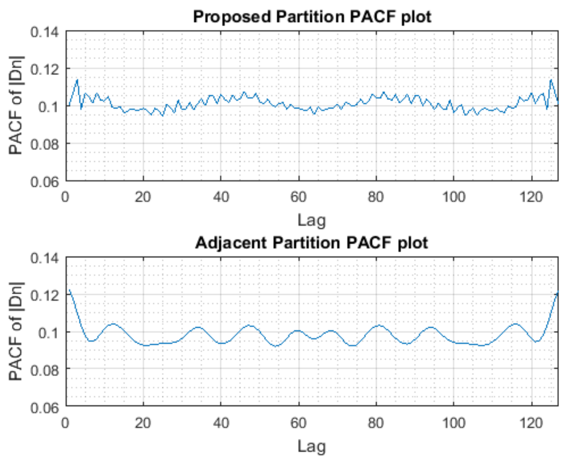


Fig. 6(b). PAPR performance comparison, for 128-subcarrier OFDM system with π/4-QPSK (−∗−) and QPSK (−∗—) mappers for various partitions ($V = 4, (b) = (b^1, b^2, b^3, b^4)$, and $b^v \in \{\pm 1, \pm j\}$).

The PAPR performance of PTS technique with the proposed, adjacent, interleaved, and pseudo-random partitioning, for OFDM system with QPSK [10] and $\pi/4$-QPSK mappers are shown in Figs. 6(a) and 6(b). It is noted that in these figures $V = 4, (b) = (b^1, b^2, b^3, b^4)$, and $b^v \in \{+1, \ +j, -1, -j\}$. It is observed that the achievable PAPR performance for both systems are the same for various partitions. These results are presented in Table V.

TABLE V: ACHIEVABLE PAPR FOR 64- AND128-SUBCARRIER OFDM SYSTEMS WITH Π/4–QPSK AND QPSK MAPPERS, ($V = 4, (b) = (b^1, b^2, b^3, b^4)$, AND $b^v \in \{\pm 1, \pm j\}$)

N	Partition type	Achievable PAPR in dB, $\pi/4 - QPSK$	Achievable PAPR in dB, $QPSK$
64	Un-Partitioned	9.88	10.181
	Proposed	5.964	6.038
	Adjacent	6.310	6.373
	Interleaved	7.349	7.362
	Pseudo-random	5.778	5.681
128	Un-Partitioned	10.687	10.758
	Proposed	6.486	6.522
	Adjacent	6.899	6.899
	Interleaved	7.97	7.755
	Pseudo-random	6.369	6.395



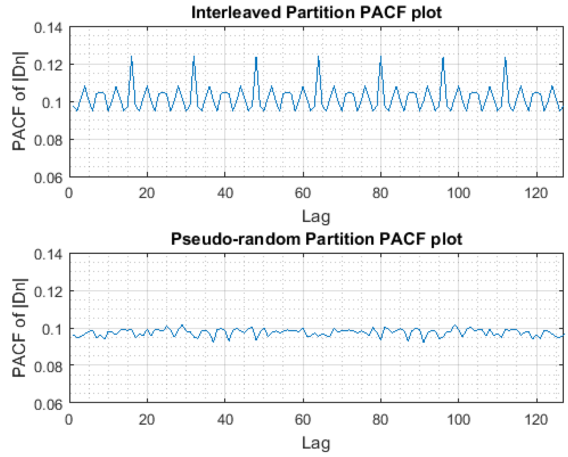


Fig. 7. PACF plots for the proposed, adjacent, interleaved, and pseudo-random partitions for 128-subcarrier OFDM system with $\pi/4$-QPSK mapper, and $\tilde{b}_2$.

In Fig. 7, periodic autocorrelation function (PACF) plots for the proposed, adjacent, interleaved, and pseudo-random partitions for 128-subcarrier OFDM system with $\pi/4$-QPSK mapper with $\tilde{b}_2$ are shown. It is noted that the PACF plot for the proposed partition technique is nearly the same as that for the pseudo-random partitioning scheme. The PACF plots for both the proposed partition and the pseudo-random partition imply symbols' independence compared to adjacent or interleaved partitions, hence yields better PAPR performance.

V. CONCLUSION

In this paper, PTS technique in OFDM system with π/4-QPSK mapper is examined for PAPR performance when different types of partitioning are used. A new partitioning scheme is proposed based on adjacent partitioning and magic squares. In addition, PAPR performance comparison for different partitions is provided for π/4-QPSK and QPSK mappers in OFDM systems. It is shown that the proposed partitioning technique is structurally simple and achieves superior performance compared to well-known adjacent and interleaved partitions in PTS technique used for PAPR reduction in OFDM systems.

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