Improvement of PAPR in OFDM Systems Using SLM Technique and Digital Modulation Schemes

Srinu Pyla, K. Padma Raju and N. BalaSubrahmanyam

Abstract Orthogonal frequency division multiplexing (OFDM) is an attractive transmission technique for high data rate and reliable communications over multipath fading channels. One of the main drawbacks in OFDM is increase in peak-to-average power ratio (PAPR) of the signal, which causes degradation of bit error rate (BER) performance, nonlinear distortion effects, and need of high-power amplifiers. To reduce PAPR, there are several distortion- and distortionless-based schemes. In this paper, distortionless-based scheme, selective level mapping (SLM), is considered for the reduction of PAPR as it gives significant improvement in PAPR. For encoding, turbo codes are used as they are a class of high-performance forward error correction (FEC) codes. This paper consists of comparison of PAPR improvement for various digital modulation techniques.

Keywords OFDM · PAPR · SLM · Turbo codes · CCDF · Digital modulation schemes

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1 Introduction

Even though there are a lot of advantages of OFDM, there are a few drawbacks, such as high peak-to-average power ratio (PAPR), inter-carrier interference (ICI), etc. High PAPR occurs when same-phase signals are added because it leads to increase in peak power and causes degradation of bit error rate (BER) performance, nonlinear distortion effects, and need of high-power amplifiers. To reduce PAPR, there are several distortion- and distortionless-based schemes. Distortion-based techniques reduce the PAPR of the OFDM symbol at the cost of adding distortion to the signal points in the subcarriers. References [1–3] describe that clipping suppresses the time-domain OFDM signals of which the signal powers exceed a certain threshold. The penalty is the significant increase in out-of-band energy (spectral broadening). Peak windowing is applied after clipping to reduce the out-of-band energy but the peak power will regrow. To avoid this, recursive clipping and filtering (RCF) is used to suppress both power and spectrum of the signal. The orthogonal frequency division multiplexing (OFDM) is very popular for its robustness against the multi path fading channels [4, 5]. It is an effective high-speed data transmission technique. OFDM is emerging as the preferred modulation scheme in modern high-data rate wireless communication systems. OFDM has been adopted in the European digital audio and video broadcast radio systems and is being investigated for broadband indoor wireless communications. Standards such as High Performance Local Area Network/2 (HIPERLAN) and IEEE 802.11a and IEEE 802.11b have emerged to support IP-based services. Such systems are based on OFDM and are designed to operate in the 5-GHz band. OFDM is a special case of multicarrier modulation. Multicarrier modulation is the concept of splitting a high-data-rate signal into a number of lower data-rate signals, modulating each of these new signals to several frequency channels, and combining for transmission [6]. In OFDM, the multiple frequencies, known as subcarriers, are orthogonal to each other. One of the principal advantages of OFDM is its utility for transmission at very nearly optimum performance in unequalized channels and in multipath channels.

The redundancy-based technique includes coding, selective mapping (SLM), partial transmit sequence (PTS), tone reservation (TR), tone injection (TI), etc. This technique avoids the undesired effects in the previous techniques at the cost of reduced transmission rate or increased average power due to the introduction of redundancy (indirect reduction in PAPR) [7–10]. Daoud and Alani stated that coding technique is used to identify the OFDM symbol with minimum PAPR. Such coding techniques offer good PAPR reduction performance and coding gain. The critical problem for the coding approach is that for the OFDM system with large number of subcarriers, either encounters design difficulties or the consequent coding rate becomes prohibitively low in [11]. The basic idea of SLM technique is to generate several OFDM symbols of same information with various phase factors as candidates and then select the one with the lowest PAPR for transmission [12–14].

In this paper, selective level mapping (SLM) is considered for reducing the probability of high PAPR. A set of independent sequences are generated with a certain criteria from the original signal, and then the sequence with the lowest PAPR is transmitted. Improvement in PAPR for various digital modulation techniques with and without SLM techniques is compared.

2 OFDM Technique

In OFDM, a block of N complex symbols (subcarriers) are transformed into time domain using the inverse fast Fourier transform (IFFT). These N subcarriers span a bandwidth of B Hz and are separated by a spacing of $\Delta f = B/N$. The continuous-time baseband representation of this is

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X[k] e^{\frac{j2\pi\Delta fkt}{T}}, t \in [0, T] \tag{1}$$

where $T = 1/\Delta f$ is the symbol period and $\{X[k]\}_{k=0}^{N-1}$ are the data symbols drawn from a constellation.

In practice, the baseband modulation is done in the digital domain using an oversampled version of $x(t)$ given by

$$x\left[\frac{n}{L}\right] = \frac{1}{\sqrt{LN}} \sum_{n=0}^{N-1} X[k] e^{\frac{j2\pi kn}{NL}},\ n \in [0, NL - 1] \tag{2}$$

where L is the oversampling factor. When $L = 1, x[n]$ is the Nyquist sampled version of $x(t)$. The data symbols are modulated by BPSK, QPSK, OPSK (8PSK), or QAM. In order to avoid inter-symbol interference (ISI), OFDM systems append a cyclic prefix (CP) to the time-domain signal. The length of the CP is set to be at least the maximum delay spread N, of the channel response. The PAPR of an OFDM signal is defined as the ratio of maximum power to the average power of the signal and is given by

$$\mathrm{PAPR} = \frac{\max\left[|x_k|^2\right]}{E\left[|x_k|^2\right]}, 0 \le k \le N - 1 \tag{3}$$

where $E\{.\}$ denotes the expected value operation and $x_k = [x_1, x_2, x_3, \ldots x_{N-1}]^T$.

$$\mathrm{PAPR\ in\ dB} = 10\log_{10}(\mathrm{PAPR}) \tag{4}$$

3 Turbo Encoder

In information theory, turbo codes are a class of high-performance forward error correction (FEC) codes and closely approach the channel capacity. Decoding of long sequence codes is possible with turbo codes, and burst errors can be detected

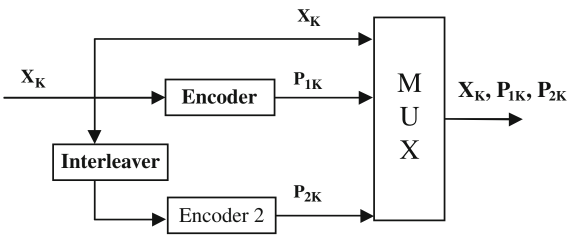


Fig. 1 Turbo encoder

and corrected by using these codes, which is not possible with other codes. The encoder for a turbo code is parallel concatenated convolutional code [12–14]. The schematic block diagram of the encoder is shown in Fig. 1, and the binary input data sequence is represented by

$$X_k = (X_1, X_2, \ldots X_N) \tag{5}$$

In this turbo encoder, the code rate is 1/3 in which for every single bit input, the output bits are three. So, the codeword is of 24 bits in length. The input sequence is processed with the help of ENCODER 1 and coded bit stream, P_{1k} is generated. The data sequence is interleaved. That is, the bits are loaded in a matrix and read out in a way so as to spread the positions of the input bits, and the bits are found to be in a pseudo-random manner. The interleaved data sequence is passed through second convolution ENCODER 2, and second coded bit stream, P_{2K} is generated. The code sequence that is passed to the modulator for transmission is a multiplexed and possibly punctured stream consisting of systematic code bits X_k and parity bits from both the encoders P_{1K} and P_{2K}. This coded data are decoded at the receiver using turbo decoder.

4 SLM Technique

In this technique, the transmitter generates a set of sufficiently different candidate data blocks with same information as the original data block and selects the most favorable for transmission. A schematic block diagram of the SLM technique is shown in Fig. 2. Each data block is multiplied by V different phase sequences, each of length N, $V(m) = \left[v_{m,0}, v_{m,1}, \ldots v_{m,N-1}\right]^T$, $m = 1, 2, \ldots M$, resulting in M modified data blocks. To include the unmodified data block in the set of modified data blocks, $V(1)$ is set as the phase vector of length N. The modified data block for the mth phase sequence is denoted as

$$X(m) = \left[X_{0,v_{m,1}}, X_{1,v_{m,2}}, \ldots X_{N-1,v_{m,N-I}}\right]^T \tag{6}$$

where $m = 1, 2, \ldots M$.

Among the modified data blocks $X(m)$, $m = 1, 2, \ldots M$, the one with the lowest PAPR is selected for transmission. Information about the selected phase sequence

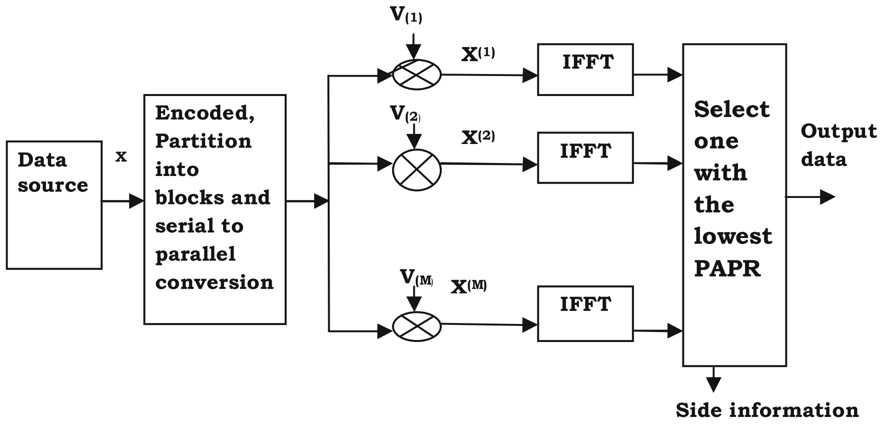


Fig. 2 Block diagram of OFDM transmitter with SLM technique

should be transmitted to the receiver as side information. At the receiver, the reverse operation is performed to recover the original data block. The SLM technique implementation needs M IFFT operations, and the number of required side information bits is $\log_2 M$ for each data block.

This approach is applicable for all types of modulation with any number of subcarriers. The amount of PAPR reduction for SLM depends on the number of phase sequences M and the design of the phase sequences.

The probability that the PAPR of the OFDM signal exceeds a certain threshold γ is given by

$$P_r\{\mathrm{PAPR}[x(n)] > \gamma\} = 1 - (1 - e^{-\gamma})^N \tag{7}$$

In SLM, it is assumed that M statistically independent alternative sequences which represent the same information are generated by some suitable means and are multiplied by various phase vectors. The sequence with the lowest PAPR is selected for transmission.

5 Digital Modulation Schemes

There are various digital modulation schemes such as amplitude shift keying (ASK), phase shift keying (PSK), frequency shift keying (FSK), etc. These are of binary and M-ary types. When the bandwidth of the channel is less than the required value, M-ary signaling schemes are preferred for maximum efficiency. In general OFDM systems are designed for high-data-rate applications, so M-ary signaling (modulation) schemes especially M-ary PSK and M-ary QAM schemes are preferred.

M-ary PSK

In M-ary PSK, the phase of the carrier takes on one of M possible values namely

$$Q_i = 2(i-1)\frac{\pi}{M} \tag{8}$$

where $i = 1, 2, \ldots M$. Accordingly, during each signaling interval of duration T, one of the M possible set is

$$\mathrm{Si} = \sqrt{\frac{2E}{T}\mathrm{COS}\left(2\pi f_c t + \frac{2\pi}{M}(i-1)\right)} \tag{9}$$

where E is signal energy per symbol f_c is carrier frequency $= n_c/T$ and n_c is an integer

If $M = 2$ (BPSK), $M = 4$ (QPSK), $M = 8$ (OPSK, or 8PSK)

Average probability of symbol error for coherent $M =$ ary PSK is

$$P_e = \mathrm{erfc}\left(\sqrt{\frac{E}{N}\sin\left(\frac{\pi}{M}\right)}\right) \tag{10}$$

Bandwidth efficiency of M-ary PSK signal is

$$\rho = \frac{R_b}{B} = \frac{\log_2 M}{2} \tag{11}$$

where B is bandwidth required to pass M-ary PSK signal and R_b is bit rate

As the number of states M is increased, the bandwidth efficiency is improved at the expense of error performance. To compensate this, E_b/N_0 has to increase.

Quadrature Amplitude Modulation

It is a combination of PSK and ASK, so-called Hybrid M-ary PSK. M-ary QAM signal for symbol k is defined by

$$s_k(t) = \sqrt{\frac{2E_b}{T}}a_k\cos(2\pi f_c t) - \sqrt{\frac{2E_b}{T}}b_k\sin(2\pi f_c t),\ 0 \ll t \ll T,\ k = 0, \pm 1, \pm 2, \ldots \tag{12}$$

The signal $s_k(t)$ consists of two phase quadrature carriers with each one being modulated by a set of discrete amplitudes and hence called quadrature amplitude modulation (QAM). Probability of symbol error is

$$P_e = 2\left(1 - \frac{1}{\sqrt{M}}\right)\mathrm{erfc}\left(\sqrt{\frac{E_0}{N_0}}\right) \tag{13}$$

where E_0 is energy of signal with lowest amplitude

$$\frac{D_{\min}}{2} = \sqrt{E_0} \tag{14}$$

where $D_{\min}$ is minimum distance between two message points. The key advantage of QAM is that it is highly spectrally efficient and supports high data rates

6 Results and Analysis

The PAPR reduction of the proposed scheme is examined by MATLAB simulation. In this scheme, an OFDM signal with $N = 256$ subcarriers with each symbol having 8 bits stream. Tables 1, 2, 3, and 4 demonstrate improvement in PAPR, in dBs for a sample of different mapping techniques with and without SLM technique. BPSK, QPSK, 8PSK, and 16QAM are used for mapping. Turbo encoder has a constraint length $K = 3$ with a code rate of 1/3. To evaluate the performance, the complementary cumulative distribution (CCDF) of PAPR for OFDM signal x is

$$\mathrm{CCDF}(\mathrm{PAPR}(x)) = P_r(\mathrm{PAPR}(x) > \mathrm{PAPR0}) \tag{15}$$

CCDF can be interpreted as the probability that the PAPR of an OFDM signal exceeds some threshold level PAPR0. PAPR0 is referred to as the symbol chip probability and determined by the amplifiers in the system. From the obtained graphs (Figs. 3, 4, 5, 6, 7, and 8), it is found that QPSK gives better improvement

Table 1 PAPR values for BPSK modulation with turbo coding

Message bits	PAPR without SLM (dB)	PAPR with SLM (dB)	PAPR improvement
00000000	13.8021	4.1470	9.6551
00000001	11.3033	3.4056	7.8977
00000010	6.1979	3.3154	2.8825
00000011	7.7815	4.5593	3.2222
00000100	7.7815	4.4820	3.2995
00000101	9.1204	4.0843	5.0361
00000110	6.9043	4.7800	2.1243
00000111	7.9502	4.1263	3.8239
00001000	4.3019	4.0837	0.2182
00001001	4.9150	3.6328	1.2822
00001010	4.3533	4.6535	0.3002

Table 2 PAPR values for QPSK modulation with turbo coding

Message bits	PAPR without SLM (dB)	PAPR with SLM (dB)	PAPR improvement
00000000	10.7918	3.4617	7.3301
00000001	8.3463	3.8730	4.4733
00000010	3.3579	2.9534	0.4045
00000011	5.2288	3.8093	1.4195
00000100	4.7712	3.6259	1.1453
00000101	6.1979	2.7662	3.4317
00000110	6.9689	4.0106	2.9583
00000111	6.3889	3.6986	2.6903
00001000	3.3579	2.5023	0.8556
00001001	5.2288	3.5118	1.717
00001010	4.2597	2.9286	1.3311

Table 3 PAPR values for 8PSK modulation with turbo coding

Message bits	PAPR without SLM (dB)	PAPR with SLM (dB)	PAPR improvement
00000000	9.0309	2.8602	6.1707
00000001	8.3207	3.5494	4.7713
00000010	3.6255	2.8320	0.7935
00000011	2.7365	2.9430	−0.2065
00000100	4.0835	2.3001	1.7834
00000101	2.8289	2.2524	0.5765
00000110	6.7570	2.7575	3.9995
00000111	6.0206	2.2414	3.7792
00001000	4.9383	1.7539	3.1844
00001001	3.0103	2.1588	0.8515
00001010	4.4467	2.6145	1.8322

Table 4 PAPR values for 16QAM modulation with turbo coding

Message bits	PAPR without SLM (dB)	PAPR with SLM (dB)	PAPR improvement
00000000	7.7815	1.7060	6.0755
00000001	6.9135	2.0295	4.884
00000010	5.3416	2.0222	3.3194
00000011	4.8467	2.2633	2.5834
00000100	2.7102	2.6780	0.0322
00000101	4.9069	1.2297	3.6772
00000110	5.4920	1.6851	3.8069
00000111	5.0021	2.5626	2.4395
00001000	3.6592	2.1985	1.4607
00001001	3.6592	2.0956	1.5636

Fig. 3 Comparison of PAPR improvement for various modulation schemes

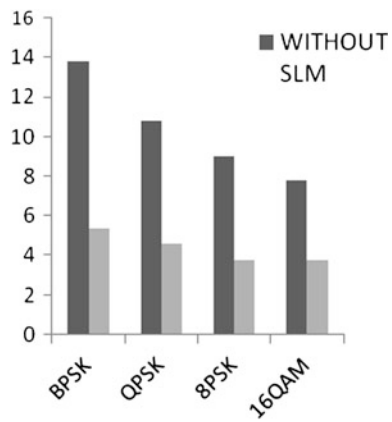


Fig. 4 CCDF of PAPR of OFDM for BPSK for $N = 256$ with and without SLM using turbo code at code rate 1/3

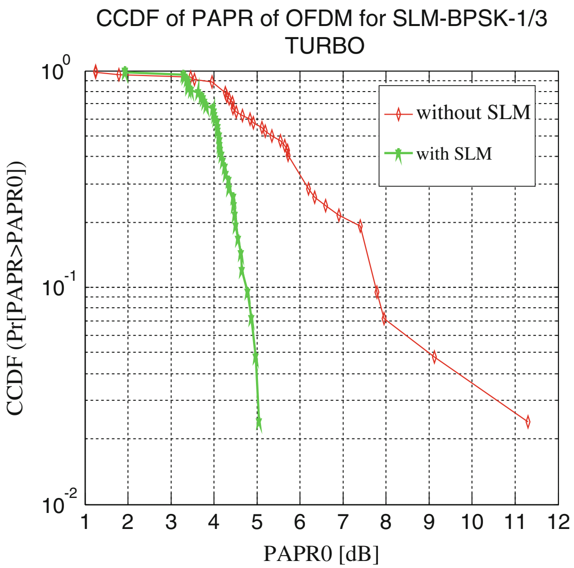
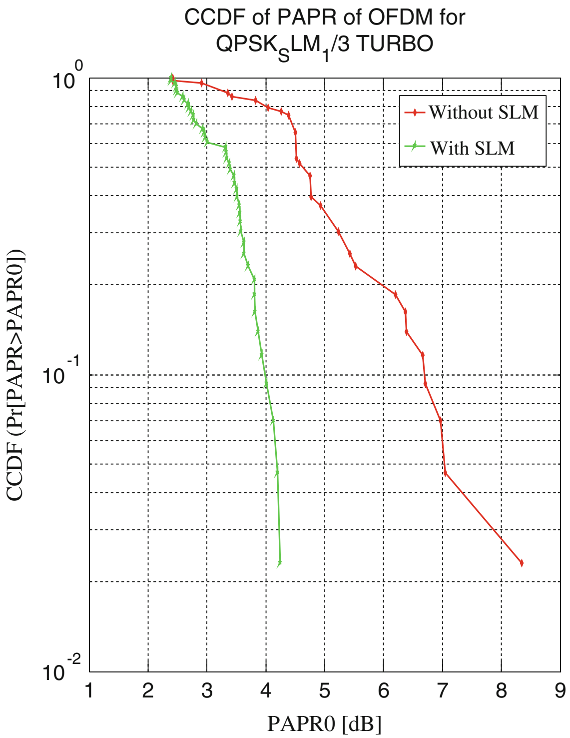


Fig. 5 CCDF of PAPR of OFDM for QPSK for $N = 256$ with and without SLM scheme using turbo code at code rate 1/3



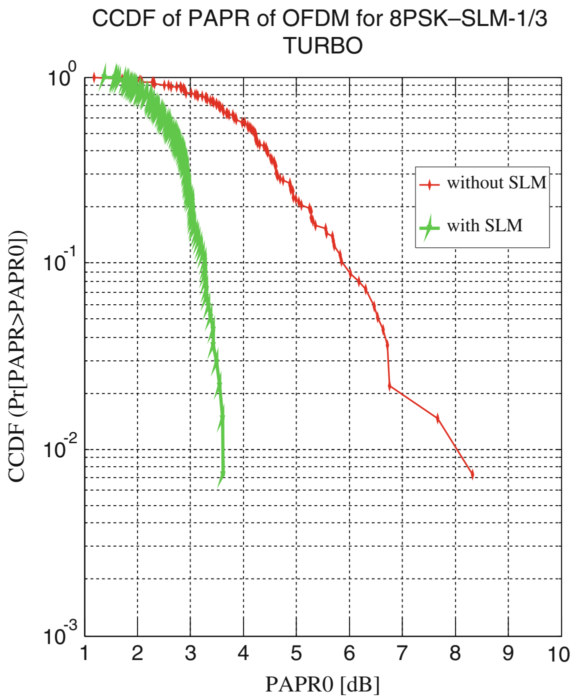


Fig. 6 CCDF of PAPR of OFDM for 8PSK for $N = 256$ with and without SLM using turbo code at code rate 1/3

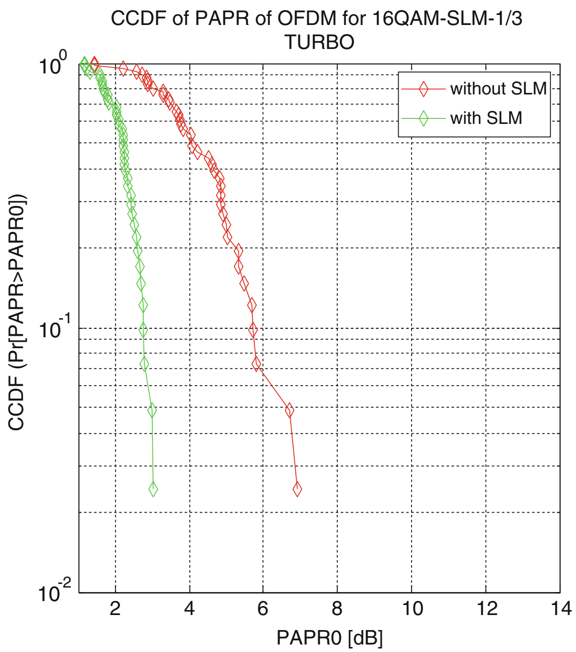


Fig. 7 CCDF of PAPR of OFDM for 16QAM for $N = 256$ with and without SLM for 16QAM using turbo code at code rate 1/3

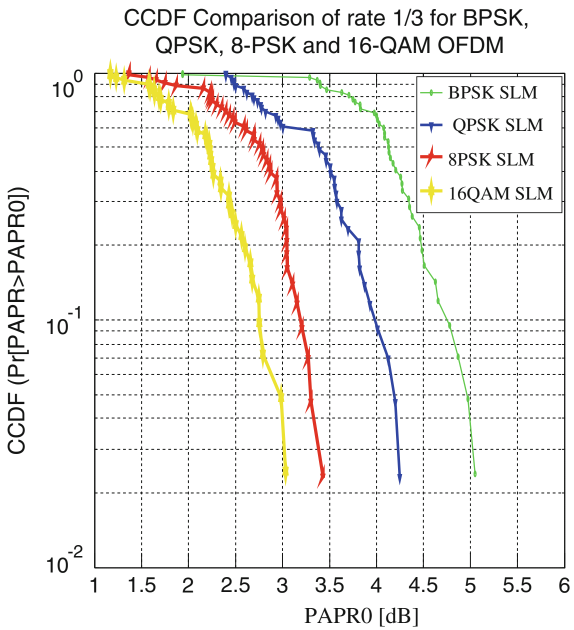


Fig. 8 CCDF of PAPR of OFDM for BPSK, QPSK, 8PSK, and 16QAM for $N = 256$ with SLM scheme using turbo code at code rate 1/3

in PAPR as phases of constellation points are mutually shifted by 90°. However, 16QAM OFDM system performance is much better with lesser power requirement compared to remaining modulation schemes for the same number of candidates because in QAM, both phase as well as amplitude are controlled. To accommodate 256 candidates, the maximum power required is 5, 3.5, 4.2, and 3 dB for BPSK, QPSK, 8PSK, and 16QAM, respectively, when SLM scheme is applied, whereas 11.5, 8.4, 8.5, and 7 units power in dB is required to accommodate the same number of candidates in the absence of SLM scheme in same order. In this investigation, it is found that in 16QAM, the slope of PAPR is very high compared to remaining schemes, and its performance is better compared to the above-mentioned schemes. The improvement in PAPR is 6.5, 4.1, 5, and 4 dB for BPSK, QPSK, 8PSK, and 16QAM, respectively (Table 5).

Table 5 Peak power values for various modulation schemes

Modulation technique	Without SLM maximum power (dB)	With SLM maximum power (dB)
BPSK	13.8021	5.4045
QPSK	10.7918	4.6005
8PSK	9.0309	3.7691
16QAM	7.7815	3.7930

7 Conclusions

Combining turbo coding and SLM techniques effectively reduces PAPR to a considerable extent compared to each of the techniques applied independently. It is evident from the results that among various digital modulation schemes, 16QAM has shown better performance as it is phase as well as amplitude sensitive, and the PAPR improvement is better for higher-order modulation schemes as throughput increases with the order of the modulation. The proposed technique can be used in applications calling for effective power management in transmitting systems like in satellite communications.

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