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SLM Transmitter and Receiver for PAPR Reduction of OFDM System

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Abstract: Orthogonal frequency division multiplexing (OFDM) also referred to as multi carrier communication systems, become a key technology in current and for future wireless communication systems. Due to OFDM's immunity to many channel imperfections, it is the ideal modulation scheme for many applications which transmit signals in hostile environments. Although, OFDM introduces major disadvantages like Peak to Average Power Ratio (PAPR), sensitivity to frequency offset. The PAPR of the transmitted signal power is large, necessitating power back off, unless PAPR reduction techniques are incorporated to control the resulting nonlinear distortion at the power amplification stage. In this paper the technique of Selected Mapping (SLM) is simulated for OFDM and it is found that using this technique with 16 alternative sub carrier vectors, PAPR is reduced to approximately 4.6 dB. But this scheme requires the transmission of the side information to indicate the used masking pattern. Hence, we should consider the reliability of this side information, which requires the high signaling overhead. So, SLM receiver based on maximum likelihood decoding that operates without side information has been implemented.

Keywords: Orthogonal frequency division multiplexing (OFDM), Peak-to-Average Power Ratio (PAPR), Selected mapping (SLM), Partial transmit sequences (PTS), Power amplifier (PA).

I. INTRODUCTION

In wireless communication, concept of parallel transmission of symbols is applied to achieve high throughput and better transmission quality [7]. Orthogonal Frequency Division Multiplexing (OFDM) is a key technology to combat multipath effects in wireless communication [7]. It has therefore been chosen as the modulation standard for IEEE802.11a/g WLAN, Worldwide Interoperability for Microwave Access (WiMax), Digital Audio Broadcasting (DAB). However major drawbacks of OFDM are: sensitivity to carrier offset and peak to average power ratio [1].

High peak values cause saturation of the power amplifier and both in-band and out-of-band distortion when limiting effects occurs. To prevent such phenomena, amplifiers are normally "backed off" by approximately the PAPR. This however severely impacts power amplifier efficiency, making it preferable to reduce the PAPR of the signal before it enters the power amplifier [1]. Selected mapping (SLM) is powerful and distortion less peak power reduction scheme for OFDM. In SLM the transmitter selects one favourable transmit signal from a set of sufficiently different signals which all represent the same information [2]. Transmitted signal can be recovered at SLM receiver that is based on maximum likelihood decoding.

II. PAPR IN OFDM

OFDM signals have a higher Peak-to-Average Power Ratio (PAPR) than single carrier signals. The reason for this is that in the time domain, a multicarrier signal is the sum of many narrowband signals. At some time instances, this sum is large, at other times it is small, which mean that the peak value of the signal is substantially larger than the average value. This high PAPR is one of the most important implementation challenges that face OFDM because it reduces the efficiency and hence increases the cost of the RF power amplifier.

Let $A = [A_0A_1\ldots..A_{N-1}]$ denote an input symbol sequence in the frequency domain, where A_K represents the complex data of the k^{th} sub carrier and N the number of sub carriers of OFDM signal. Let T be a period of input symbol and NT a period of OFDM signal. The OFDM signal is generated by summing all the N modulated sub carriers each of which is separated by 1/T.

Then the complex OFDM signal in time domain is expressed as

$$a_t = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} A_n e^{i2\pi nt/NT}, 0 \le t \le NT \quad (1)$$

Where, t is continuous time index. The OFDM signal sampled at Nyquist rate can be written as

$$a_k = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} A_n e^{j2\pi k/N}, k = 0,1,\ldots, N-1 \quad (2)$$

Which can also be in a vector form, called an OFDM signal sequence, as $a = [a_0 a_1 \ldots a_{N-1}]$. In fact, a correspond to inverse fast Fourier transform (IFFT) of A. The PAPR of OFDM signal sequence a is defined as the ratio between maximum instantaneous power and its average power, which can be written as,

$$PAPR(a) = \frac{\max_{0\le k\le N-1} |a_k|^2}{E\left[|a_k|^2\right]} \quad (3)$$

Where E[.] denotes the expectation operator [3].

Statistically it is possible to characterize the PAPR distribution (probability that PAPR exceeds given

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threshold γ) using its cumulative distribution function (CDF) or complementary cumulative distribution function (CCDF). For the case of OFDM, the following expression for the CCDF holds,

$$P_r\left(PAPR < \gamma\right) = 1 - \left(1 - \exp\left(-\gamma\right)\right)^N$$
$$CCDF_{PAPR} = 1 - CDF_{PAPR} \qquad (4)$$

III. THE PAPR PROBLEM

When a high peak signal is transmitted through a nonlinear device such as a high power amplifier (HPA) or digital-to-analog converter (DAC), it generates out-of-band energy (spectral regrowth) and in-band distortion (constellation tilting and scattering). These degradations may affect the system performance severely. The nonlinear behavior of HPA can be characterized by amplitude modulation-amplitude modulation (AM/AM) responses. Fig. 1 shows a typical AM/AM response for a HPA, with the associated input and output back off regions.

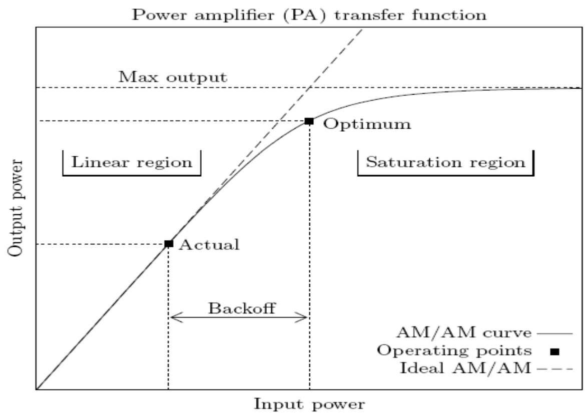

Fig. 1 A typical AM/AM response for a HPA

The drive power at which the output power saturation occurs is called the input saturation power. The ratio of input saturation power to desired drive power is called the amplifier input backoff.

$$\beta_{in} = 10\log_{10}\left(P_{in,sat} / P_{in}\right) \qquad (5)$$

Increasing input backoff, produces less output power but improves the linearity of the device, since the degree of nonlinearity is reduced. The choice of the input backoff presents a trade-off between linear behaviour and power efficiency. The power efficiency of a HPA can be increased by reducing the PAPR of the transmitted signal. It would be desirable to have the average and peak values are as close together as possible in order to maximize the efficiency of the power amplifier. In addition to the large burden placed on the HPA, a high PAPR requires high resolution for both the transmitter's digital-to-analog converter (DAC) and the receiver's ADC, since the dynamic range of the signal is proportional to the PAPR. High resolution D/A and A/D conversion places an additional complexity, cost, and power burden on the system. So, for cost reduction and high power efficiency of the devices, different PAPR reduction techniques are developed.

IV. PAPR REDUCTION TECHNIQUES

OFDM signal consists of a number of independently modulated sub carriers, which can give a large PAPR when added up coherently. When N signals are added with the same phase, they produce a peak power that is N times the average power which produce a peak to average power ratio (PAPR) problem. It is difficult to classify all the effort for reducing PAPR for multicarrier data transmission. The following Fig. 2 is probably the most commonly accepted classification of many PAPR reduction techniques. At the higher level this classification divides the methods into PAPR reduction with distortion and PAPR reduction without distortion.

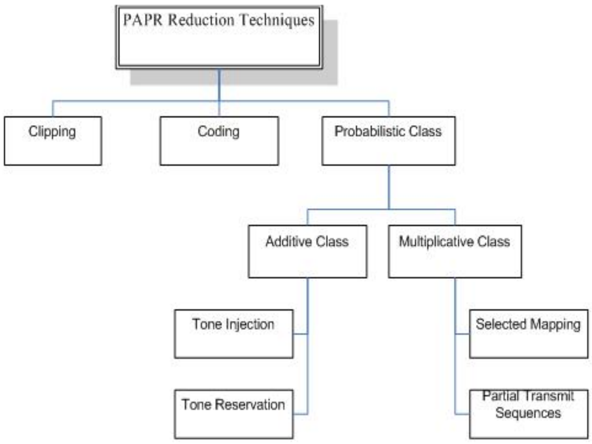

Fig. 2 classification of PAPR reduction techniques

Factors to be considered before a specific PAPR reduction technique is selected

- PAPR reduction capability
- Power increase in the transmitted signal
- BER increase at the receiver
- Loss in data rate
- Computational Complexity

1 Clipping

The proposal is made to apply clipping to the over sampled signal that causes out of band interference. This interference is taken care of by a FIR filter that also removes the side lobes of the modulation pulse. However, the filter leads to new amplitude peaks in the signal; but after all, the peak to average power ratio of the signal is reduced by this method. Fig. 3 shows clipping of samples above threshold level.

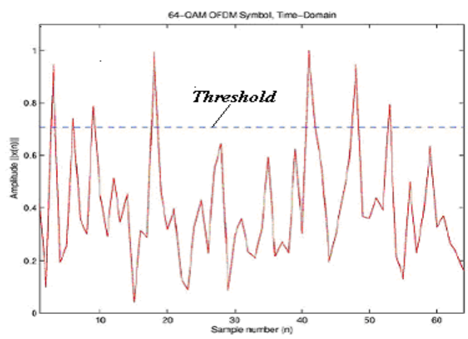

Fig. 3 clipping of samples above threshold

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2 Coding Techniques

The basic idea of these techniques is to avoid the transmission of symbols that present a high PAPR, which in fact is equivalent to use redundant codes. Many coding techniques have been proposed. In some of them introduced redundancy is also interestingly used for error detection or correction. Among all the used codes, one may mention Golay sequences, M sequences and Reed Muller codes. The main drawback of all these coding schemes is that the computational complexity which can be very high when the number of carriers is relatively large.

3 Probabilistic Schemes

The final class of techniques is classified as probabilistic. They do not aim at reducing the maximum signal amplitude, but rather the occurrence of peak values. As a consequence, the clipping noise is reduced. The basic idea is thus to modify the function P(δ) to P'(δ) in such a way that large values occur with a lower probability. The general probabilistic approach is to introduce some limited redundancy. This resembles block coding, but the goal is not to eliminate the peaks, but only to make them less frequent. The basic way to achieve this is by a linear transformation. In this equation, Yn are elements of the N-point input vector Y of the IFFT and Xn are elements of the original frequency domain data vector X.

$$Y_n = A_n \cdot X_n + B_n, 1 \le n \le N \quad (6)$$

The goal is to find the N-point vectors A and B with elements an and Bn respectively, such that the transmit symbol y = IFFT(Y) has a small probability of peaks. Selected Mapping (SLM) and Partial Transmit Sequences (PTS) try to select a good A, while B is equal to the zero vectors. They both use the restriction that the N components of A all have unit amplitude:

$$A_n = e^{j\theta_n}, \theta_n \in [0, 2\pi), 1 \le n \le N \quad (7)$$

This results in a pure rotation vector. Tone Injection (TI) and Tone Rejection (TR) optimize B, while A is set to the all-one-vector. Each of these four techniques has a different performance versus overhead and complexity trade-offs [4]-[6].

Tone Injection (TI) uses an additive correction, which means that it optimizes B in Eq.6. The basic idea is to extend the QAM constellation, such that the same data point corresponds to multiple possible constellation points. One option in this class is illustrated in Fig. 4, where the original shaded constellation is replicated into several alternative ones. B is therefore translation vector, such that (Y)mod = X. The receiver only needs to know how to map the redundant constellations on the original one, but no extra side information is required. On the flip side, the alternative constellation points have an increased energy compared to the original ones. The calculation of the optimal translation vector of size N is too complex. An iterative algorithm is proposed instead. Each iteration step selects a translation for one tone, such that the PAPR reduction is as large as possible and the extra power is minimized. The corrections are applied on y immediately, without having to do IFFT on each iteration.

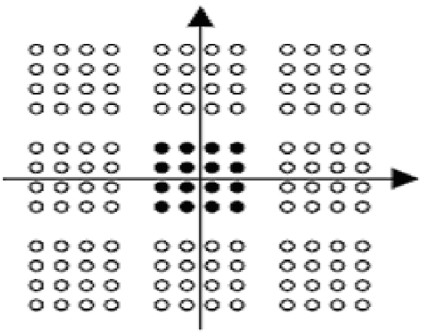

Fig. 4 TI Extended Constellation

Tone Reservation (TR) method involve not sending data over a certain set of sub- carriers (also called tones), and instead designing a signal in these bands that reduces the PAPR of the system. While using subchannels for PAPR reduction rather than sending data seems undesirable, in some applications, certain subchannel frequencies are not used for data transmission anyway and are thus available for this purpose. Therefore, a data-rate reduction is also a cost factor to be considered if a tone reservation technique is used. This method is less complex because just one time IFFT operation is needed and no need of side information. TR also requires the receiver to know the location of the reserved tones so as to disregard them when decoding the data signal. Application where data rate is prime consideration this method is not used [4]-[6].

Selective mapping (SLM) and **Partial transmit sequence (PTS)** reduce the PAPR by generating U alternative subcarrier vector that are statistically independent OFDM symbols for a given data frame and transmitting $\tilde{u}$ th symbol with the lowest peak power. The value of scheme selects a signal with minimum PAPR from a set of $\tilde{u}$ (side information) is required to recover the signal successfully. Clearly, $\log_2(U)$ bits are required to represent this information, which is of critical importance to the receiver. One solution is to reserve several subcarriers (i.e., pilot tones) for side information. In a frequency-selective fading channel, such pilot tones may be lost and an irrecoverable decoding error can occur. Extra protection bits may need to be sent and the total redundancy can thus exceed $\log_2(U)$ bits. SLM & PTS has the following disadvantages:

1) Require the side information
- In both scheme, it requires the transmission of the side information to indicate the used masking pattern. Hence, we should consider the reliability of this side information, which requires the high signaling overhead.

2) Complexity issue
- Moreover, both schemes need multiple IFFT operation.

3) Additional Receiver Operation is needed
- In both scheme, detection of the masking pattern is needed for recovery of data stream from the Received signal i.e., masked data stream.

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V. PROBABILISTIC METHOD – SLM

In this most general approach it is assumed that U statistically independent alternative transmits sequences $a_\mu^{(u)}$ represent the same information. Then, that sequence $\tilde{a}_\mu = a_\mu^{(\tilde{u}_\mu)}$ with the lowest PAPR, denoted as $\tilde{\chi}_\mu$, is selected for transmission. The probability that $\tilde{\chi}_\mu$ exceeds χ_0 is approximated by,

$$P_r\left\{\tilde{\chi}_\mu > \chi_0\right\} = \left(1-\left(1-e^{-\chi_0}\right)^D\right)^U \quad (8)$$

Because of the selected assignment of binary data to the transmit signal, this principle is called selected mapping. A set of U markedly different, distinct, pseudo-random but fixed vectors,

$$P^{(u)} = \left[P_0^{(u)},\ldots,P_{D-1}^{(u)}\right]$$

$$P_v^{(u)} = e^{+j\varphi_v^{(u)}}, \varphi_v^{(u)} \in [0,2\pi), 0 \le v < D, 1 \le u \le U \quad (9)$$

must be defined. The subcarrier vector A_μ is multiplied subcarrier wise with each one of the U vectors $P^{(u)}$, resulting in a set of U different subcarrier vectors $A_\mu^{(u)}$ with components,

$$A_{\mu,v}^{(u)} = A_{\mu,v} \cdot P_v^{(u)}, 0 \le v < N, 1 \le u \le U \quad (10)$$

Then, all U alternative subcarrier vectors are transformed into time domain to get $a_\mu^{(u)} = IFFT\left\{A_\mu^{(u)}\right\}$ and finally that transmit sequence $\tilde{a}_\mu = a_\mu^{(\tilde{u}_\mu)}$ with the lowest PAPR $\tilde{\chi}_\mu$ is chosen. The SLM-OFDM transmitter is depicted in Fig. 5 where it is visualized that one of the alternative subcarrier vectors can be the unchanged original one. Optionally, differentially encoded modulation may be applied before the IFFT and right after generating the alternative OFDM symbols.

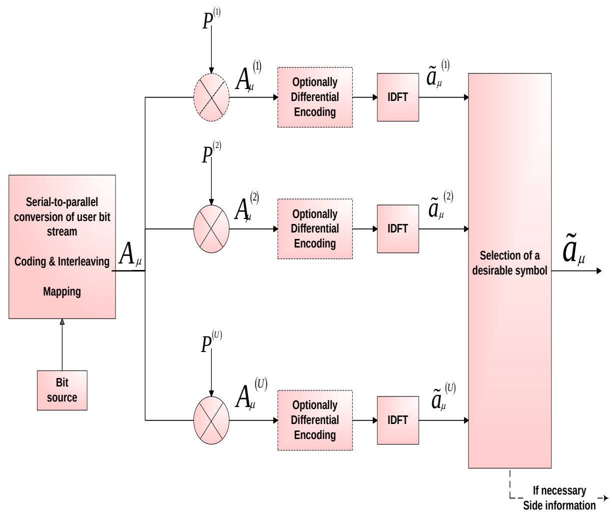

Fig. 5 PAPR reduction in SLM-OFDM

At the receiver, differential demodulation has to be implemented right after the FFT [2]. At the receiver side, reverse steps is required to recover the original signal.

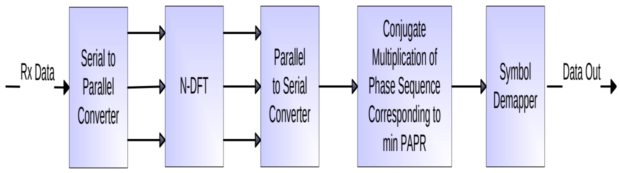

Fig. 6 Block diagram of SLM receiver

Fig. 6 shows block diagram of OFDM-SLM receiver. SLM require that the receiver has knowledge about the generation of the transmitted OFDM signal in symbol period μ . In SLM the number $\tilde{u}_\mu$ of the selected $P^{(\tilde{u}_\mu)}$ has to be transmitted to the receiver unambiguously so that this one can derotate the sub carriers appropriately. The number of bits required for canonical representation of this side information is the redundancy R_{ap} introduced by the SLM PAPR reduction scheme. As this side information (SI) is of highest importance to recover the data, it should be carefully protected by channel coding. In SLM Rap = $\log_2 U$ bits are required for side information [2].
Increasing the SLM order U, reduces the PAPR but increases the size of side information (SI). In order to transmit the SI some power and bandwidth are needed, those are taken from the total power and bandwidth budget and thus lowering the capacity. On the other hand the reduced PAPR improves the power amplifier (PA) efficiency, thus increases the channel capacity.

VI. CAPACITY ANALYSIS

The PA is fed a power of P_s from its power supply. The power emitted by the PA equals to:

$$P_{out} = \eta P_s$$

Where η denotes the PA power efficiency. It is assumed that the transmission is lossless therefore the power Signal-to-Noise Ratio (SNR) at the input of the receiver is

$$\text{SNR} = P_{out}/\sigma_n^2 \quad (11)$$

where σ_n^2 is the Gaussian noise power within the bandwidth B , the bandwidth of the transmitted signal. Let χ_0 denote the PAPR when there is no PAPR reduction. In the worst case
$\chi_0 = \text{N}$, where N is the number of OFDM sub-carriers. Let
χ_1 denote the maximal value of PAPR and R <1 denote the factor of bit rate reduction, due to some distortion less PAPR reduction scheme, i.e., the payload bit rate is $R \cdot C_T$, where
C_T is the total bit rate available. The bit rate $(1-R)\cdot C_T$ that should be sacrificed to reduce PAPR may depend on SNR or may not [10].
The efficiency η of PA depends on the PAPR χ and the efficiency increases monotonically as the PAPR decreases.

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The specific relationship $\eta = \eta(\chi)$ depends on the class of the PA and on its particular design. The theoretical efficiency upper limits for PA are graphically given in Fig.7 and by numerical computations may be curve fitted by:

$$\eta = \mathrm{G} \cdot \exp(-g\chi_{dB}) \quad (12)$$

where for class A amplifier, G = 58.7%; g = 0.1247 and for class B G = 90.7%; g = 0.1202 . χ_{dB} stands for PAPR in dB. Our argument holds for any other description of η as long as it is a decreasing function of PAPR [9] [10].

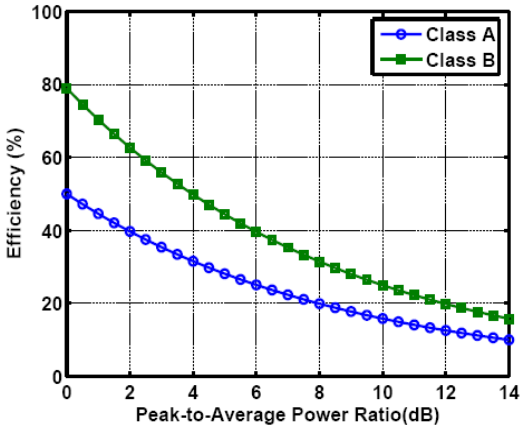

Fig. 7 Linear amplifier theoretical efficiency limits [11]

The capacity, when there is no PAPR reduction, is:

$$C_0 = \mathrm{B}\log_2(1+SNR_0) \quad (13)$$

where $\mathrm{SNR}_0 = \eta_0 P_s / \sigma_n^2$ and η_0 is the efficiency of the PA for χ_0.When SLM PAPR reduction method is applied, the capacity of a subcarrier equals to:

$$C_1' = (B/N)\log_2(1+SNR_1) \quad (14)$$

where $\mathrm{SNR}_1 = \eta_1 P_s / \sigma_n^2$ and η_1 is the efficiency of the PA for χ_1 , $\chi_1 < \chi_0$. The capacity of the whole OFDM signal is a sum of N subcarriers capacities C_1' . The capacity of the payload is therefore

$$C_1 = RB\log_2(1+SNR_1) = R \cdot C_T \quad (15)$$

where bit rate reduction factor $R = \frac{1}{N}\left(N - \frac{\log_2 U}{R_c}\right)$, and R_c is the code rate used for SI.

Let: $\lambda = SNR_1/SNR_0 = \eta_1/\eta_0 \quad (16)$

denote the SNR increase factor. As mentioned, $\eta = \eta(\chi)$ is a decreasing function therefore $\eta_1 > \eta_0$ and thus $\lambda > 1$.

From Eq. (15) and (16) we have capacity for payload is

$$C_1 = RB\log_2(1+\lambda SNR_0) \quad (17)$$

For some certain given SNR_0 or η_0, there may exists an optimal SLM order U for which C_1 is maximal. Increasing the SLM order U, above the optimal value, will only reduce the channel capacity [9] [10].

VII. SLM RECEIVER

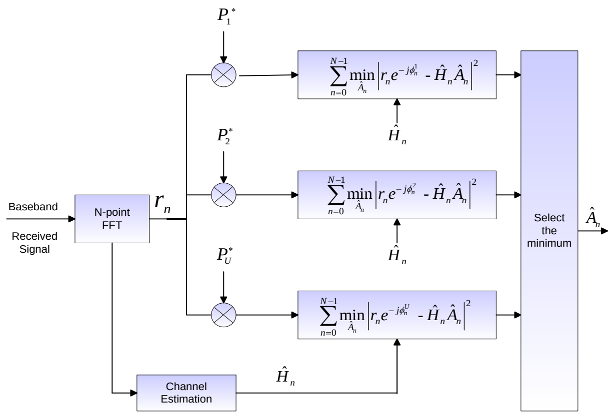

Fig. 8 SLM decoder structure [12]

The SLM encoder uses U vectors (SLM vectors) given by $\mathrm{P}_u = \left[e^{j\phi_0^u}, e^{j\phi_1^u}, \ldots, e^{j\phi_{N-1}^u}\right]$ Where $\phi_n^u \in (0, 2\pi]$ and $u \in \{0,1,\ldots,U-1\}$. For a given input frame A, the lowest PAPR sequence $A \otimes \mathrm{P}_{\tilde{u}}$, $\tilde{u} \in \{0,1,\ldots,U-1\}$ is selected for transmission. In the subsequent development, the value of the optimal transmit sequence number $\tilde{u}$ is "NOT" transmitted to the receiver. We derive the new decoder using the following properties.

1) A_n 's are restricted to a given signal constellation Q.

2) The set of P_u 's is fixed and known a priori.

3) $A \otimes \mathrm{P}_u$ and $A \otimes \mathrm{P}_v$ are sufficiently different for $u \neq v$. Fig. 8 shows block diagram of SLM decoder.

The necessary condition for this method to work is $A_n e^{j\phi_n^u} \notin \mathrm{Q}$ for all n and u. The set of P_u can be chosen readily to ensure this. For simplicity, let us assume a distortion less and noiseless channel. Now, the receiver $\mathrm{r} = A \otimes \mathrm{P}_{\tilde{u}}$ and computes $\mathrm{r} \otimes \mathrm{P}_u^*$ for $u = 0,1,\ldots,U-1$.Note that $\mathrm{r} \otimes \mathrm{P}_u^*$ will not be a vector of symbols from the constellation Q unless $u = \tilde{u}$. This observation allows us to dramatically reduce the complexity of the ML decoder.

Consider the received signal r_n after the FFT demodulation at the receiver

$$\mathrm{r}_n = H_n A_n e^{j\phi_n^{\tilde{u}}} + n_n \quad (18)$$

Where Hn is the frequency response of the channel at the n[th] subcarrier and n_n is a complex Additive White Gaussian Noise (AWGN) sample. The signal-to-noise ratio (SNR) is defined as $\gamma_s = E\left\{|H_n A_n|^2\right\} / E\left\{|n_n|^2\right\}$ where $E\{\ \}$ is the statistical expectation operator. Let r=$[r_0, r_1, \ldots, r_{N-1}]$ and H=$[H_0, H_1, \ldots, H_{N-1}]$. Without side information (not knowing $\tilde{u}$) the optimal ML decoder uses the decision metric

$$D_{SLM} = \min_{P_{\tilde{u}},\ \tilde{u}\in\{0,1,\ldots,U-1\}} \sum_{n=0}^{N-1} \min_{\hat{A}_n \in Q} \left| r_n e^{-j\phi_n^{\tilde{u}}} - \hat{H}_n \hat{A}_n \right|^2 \quad (19)$$

This minimization can be performed as follows. Let r_n be detected into the nearest constellation point $\hat{A}_n$, by comparing r_n with $H_n A_n e^{j\phi_n^{\tilde{u}}}$, where $\hat{H}_n$ is the estimated channel response. That is, a hard decision is made for each subcarrier. This whole process is repeated for $0 \le \hat{u} \le U-1$. The minimum Euclidean distance solution yields the data sequence. Fig. 8 depicts the proposed decoder structure. SLM vectors for the proposed system are constructed by selecting each ϕ_n^u randomly between 0 and 2π, subject to the constraint that $e^{j\phi_n^u}$ is not a member of Q [12].

VIII. DESIGN AND SIMULATION RESULT

The OFDM system is implemented using MATLAB to allow various parameters of the system to be varied and tested. The following OFDM system parameters are considered.

Mapping: 16- QAM
Number of data sub-carriers: 52
Number of FFT points: 64
U alternative sub carrier vectors: 16
Channel Mode: AWGN
Data rate : 54 Mbps
Total no. of symbols to Tx.: 10000

The 64 point IFFT mapping is shown in Fig. 9. For generation of real output, IFFT mapping is done by taking its conjugate.

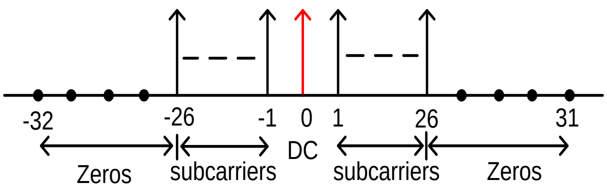

Fig. 9 IFFT mapping for Complex time output OFDM signal

Fig.10 shows the complementary cumulative distribution function (CCDF) of PAPR for the conventional SLM scheme with U = 2, 4, 8, 16. Results for OFDM symbol are shown in Table 1. It is found that using 16 alternative sequences 4.6 dB PAPR reduction can be achieved. As we increase alternative sequences order, PAPR still reduces but complexity increases at transmitter because number of IFFT calculation increases. Redundancy also increases as SLM order increases. Theoretical PAPR of N-carrier OFDM symbol can be approximated by

$$P_r\{PAPR > PAPR_0\} = 1 - \left(1 - e^{-PAPR_0}\right)^N$$

Table 1: Result of SLM with U = 2, 4, 8, 16

OFDM Symbol	PAPR Original	PAPR U = 2	PAPR U = 4	PAPR U = 8	PAPR U =16
1	6.7336	6.5184	6.5184	5.0954	5.0954
10	6.5363	4.8622	4.8622	4.8622	4.8622
100	6.0818	6.0818	6.0818	4.9694	4.7575
500	7.7899	6.6272	5.6161	5.6161	5.3308
1000	7.8618	6.1215	5.7141	5.1228	5.1228
10000	8.5178	6.5770	5.1680	4.7484	4.5734

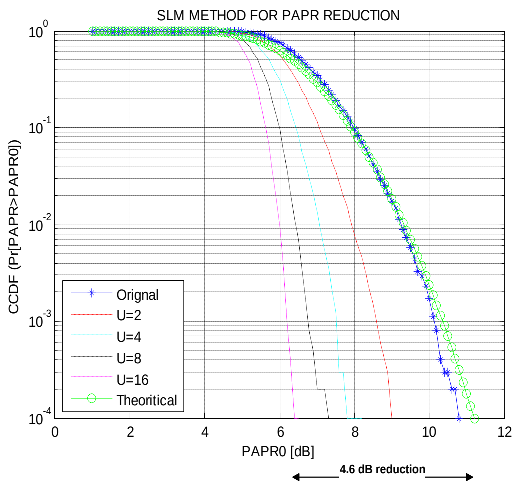

Fig. 10 CCDF plot for SLM method

By using Eq. (11) to (17) and following data, we can illustrate how channel capacity depends on the SLM order: (i) N = 52 subcarrier with 64 point IFFT, (ii) Rc = 0.5, (iii) class A amplifier, (iv) SNR_0 = 10 dB, (v) U = 16, (vi) exceeding probability for definition: 10^{-4}. Fig. 11 shows the normalized capacity C_1/B as a function of U using the above parameters, for different SLM orders.

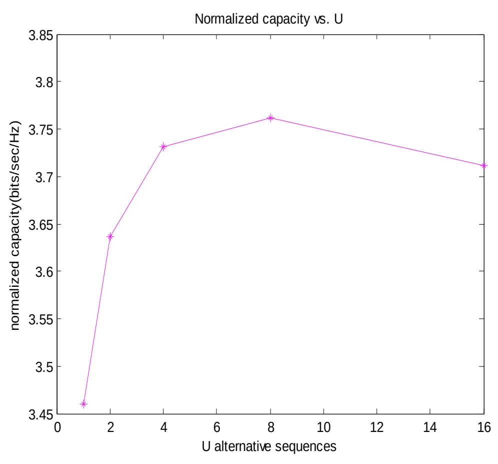

Fig. 11 Channel capacity for SLM method

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Increasing the SLM order reduces the PAPR, improves the HPA efficiency, thus increases the channel capacity, but also increases the size of side information (SI). In order to transmit the SI some power and bandwidth are needed, those are taken from the total power and bandwidth budget and thus lowering the capacity. Accordingly maximal value of channel capacity is expected as well as an optimal SLM order. From Fig. 11,U_{opt} = 8.
Results for probability of error at SLM receiver for different value of Eb/No are shown in Table 2.

Table 2: Result of BER performance of SLM decoder

Eb/No	Original P_{e1}	SLM P_{e2}
1	0.2437	0.3865
2	0.1542	0.2938
3	0.1344	0.1740
4	0.1135	0.1635
5	0.0760	0.1271
6	0.0677	0.0708
7	0.0354	0.0416
8	0.0197	0.0239
9	0.0093	0.0093
10	0.0031	0.0020

SLM receiver based on maximum likelihood decoding operates without side information. For that pilot is basically a reference carrier which is known at the receiver end in terms of position or sequence/pattern and used for the channel estimation because it provides channel state information as it has undergone the most recent channel behavior. A channel estimate is only a mathematical estimation of what is truly happening in natural environment.
Channel Estimation

- Allows the receiver to approximate the effect of the channel on the signal to eliminate it.
- Is essential for removing inter symbol interference and noise.
- Is used in diversity combining, Maximum Likelihood (ML) detection, angle of arrival estimation etc.

The values of channel in between the samples can then be obtained via interpolation procedure. Interpolation increases the number of estimated pilot samples to estimate the channel in a better way.

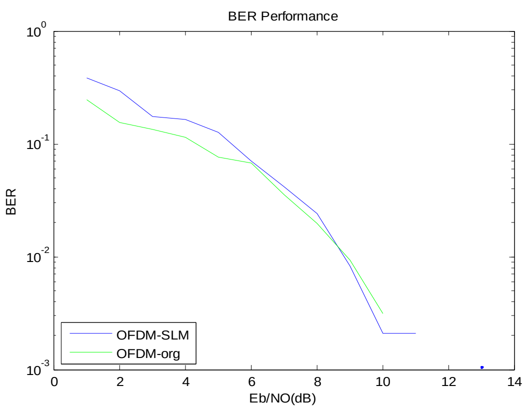

Fig. 12 BER plot for SLM receiver

For SLM receiver we have used 48 subcarriers, 4 pilot carriers with comb-type arrangement and Spline Cubic Interpolation (SCI). The SCI method produces a smooth and continuous polynomial, fitted to given data points (interp1 function with spline method is available in MATLAB). Fig. 12 shows BER performance of SLM receiver based on ML decoding operates without side information.

IX. CONCLUSION

Increasing the SLM order reduces the PAPR but increases the size of side information (SI). Some bandwidth is needed to transmit SI, thus lowering channel capacity. On the other hand, the reduced PAPR improves the HPA efficiency, thus increases the channel capacity. An optimal number of SLM candidates for which the channel capacity reaches its maximum value is U_{opt} = 8.
Simplified maximum likelihood (ML) decoder for SLM that operates without side information is proposed. SLM system with ML decoding neither lose throughput due to side information nor degrade bit error rate (BER) due to errors in side information. However, a reduction in throughput occurs due to pilot tones used for channel estimation. Some increase in receiver complexity is the price paid for these benefits.

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