OFDM TRANSMITTER AND RECEIVER PERFORMANCE IMPROVEMENTS FOR SMALL FORM FACTOR SDR HAND-HELD RADIOS

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ABSTRACT℘

OFDM exhibits high peak-to-average power ratios (PAPR) which requires high power amplifier (PA) backoff at the transmitter to minimize spectral regrowth due to clipping of the high signal peaks of the OFDM waveform. PA backoff is often also necessary to minimize receiver bit error rate (BER) degradations due to the interference induced from the PA spectral regrowth. This work utilizes two transmitter mitigation techniques to improve transmit spectral quality, which also improves receiver demodulation performance. We propose using both PAPR reduction and PA pre-distortion (linearization) to provide performance improvements. We use a novel OFDM waveform which superimposes known joint synchronization pilot sequences (JSPS) to provide PAPR reduction capability, while utilizing a piecewise linear polynomial (PWLP) pre-distortion (linearization) technique to provide further reductions in spectral regrowth. We also show that optimal placement and power (OPAP) of the pilot sequence provides further improvements in receiver BER performance over uniformly spaced constant power (USCP) pilot schemes common today in many OFDM commercial standards. We demonstrate that greater than 10 dB reduction in spectral regrowth is possible from the emitted transmit spectrum, while the combined effect of PAPR reduction, predistortion (linearization), and pilot optimization provides greater than a 4 dB improvement in received data constellation variance.

1. INTRODUCTION

Orthogonal Frequency Division Multiplex (OFDM) is well-known to provide high bandwidth efficiencies and low receiver equalization complexity in multipath channels [1]. OFDM provides high bandwidth efficiencies by overlapping data and pilot sub-carriers in an orthogonal fashion in the frequency domain with minimal spacing. High data rates are achieved in severe multipath channels, even with low receiver equalization complexity. This is accomplished by utilizing longer symbols in time, where all data and pilot symbols are synthesized as a sum of complex sinusoids and prepended with a cyclic extension at the beginning of each OFDM symbol to preserve orthogonality by preventing intersymbol interference (ISI) to occur from symbol to symbol. If the cyclic extension for each OFDM composite symbol is longer than the largest channel (multi-path) delay, then only flat fading will result. In this case, the receiver must track only one channel tap per sub-carrier, simplifying the receiver equalization complexity.

However, synthesizing multiple sub-carriers within the same symbol time also has a significant drawback. When multiple carrier frequencies are summed, the peak-to-average power ratio (PAPR) of the composite symbol can be large. If the produced peaks are subject to clipping, harmonic distortions are formed, and these distortions can interfere with in-band and out-of-band communications. Hardware (HW) mitigation of the effects of PAPR include 1) designing a transmitter power amplifier (PA) with a large linear region and 2) internal back off of transmit signal power to reduce the chances of the transmit signal peaks being clipped in the compression region of the PA. However, both HW mitigation options lead to reduced power efficiency by placing the average power of the signal below the compression region of the PA. For maximum power efficiency, the average power of the transmit signal needs to be near the compression region of the PA.

This work investigates improvements for OFDM when maximum link range and low receiver bit error rates are desired. Digital signal processing techniques offer other mitigation options. These options include 1) reduction of the PAPR characteristic and 2) pre-distortion of the transmit digital signal before entering the DAC. In this work we investigate the transmit spectral quality and receiver performance improvements using PAPR reduction and digital base-band pre-distortion.

The topic of PAR reduction has received significant attention in the literature in the recent years. Many techniques have been proposed, which in general can be considered either distortionless or alternatively will induce some distortion onto the transmitted signal. Some distortionless-based methods include coding [2], tone reservation [3-4], tone

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injection [3], selected mapping [5] and partial transmit sequence [6] methods. PAR reduction with distortion may include companding [7], transmit filtering [8] or clipping [9]. Blind selected mapping approaches have been proposed as well [10], which minimize transmit overhead. Upon inspection of the various methods listed, different tradeoffs between additional transmit overhead, algorithmic complexity and PAPR reduction performance will be apparent. In this work the PAPR reduction method is a blind technique based on the method described in [11].

Linearization is also a popular approach to mitigating non-linear transmit power amplifier effects on the OFDM signal, of which there are many proposed techniques. Comonly a signal is “pre-distorted” in a manner such that the combined effect of this pre-distortion (PD) and non-linear PA response becomes linear. This enables the average power of the signal of interest to operate closer to the PA compression region, maximizing power efficiency. Our desire is to focus on base-band PD methods in the digital domain that perform well but are of low complexity.

The amount of research activities on linearization methods is vast, including both analogue and digital techniques. Feedforward and Cartesian loop feedback linearization [12] are examples of analogue linearization using modification through the analogue componentry. Digital linearizers are primarily pre-distortion (PD) based. Look-up table (LUT) based digital PDs have been proposed [13], but can be limited by the slow adaptation due to large table sizes. This is specifically true when memory effects of the PA must be considered. Parametric PD models have also been proposed which utilize a polynomial function or a piecewise linear function to accurately characterize the PA non-linearity [14]. Compared to the LUT-based PD, the number of adaptive parameters are much less, which is attractive for hardware implementation. Digital PD is considered better than analogue schemes because it offers more flexibility and is much more suited to adaptive means. Furthermore digital PD is more robust because the linearization performance can automatically adjust or adapt to changes in manufacturing tolerance of the analogue portion of the transceiver, which is much more difficult to compensate for in analogue linearization methods.

In this work, we focus on implementing the digital PD technique introduced in [15] where a parametric model is assumed and uses a simplicial canonical piecewise linear (SCPWL) function, which is suitable for modeling memoryless nonlinearities, but still exhibits low complexity. We base our SCPWL function on actual PA data from lab measurements and then perform a SCPWL parametric fit to the lab data. The PA we utilize for the lab measurements is a state of the art PA designed for 2 watts of power output.

The OFDM waveform utilized for our evaluation is an optimized waveform as described in [11] using the pilot optimization technique described in [16]. The optimizations of the OFDM waveform include minimizing the MSE of the distance between the true symbol and the receive-side estimate. Before amplification, we apply a PAR reduction technique as well as PA pre-distortion. We have shown equivalence between the distortion characteristics caused by the PA model and the distortion caused by the actual state of the art PA hardware. Consequently, we can utilize the PA model for this evaluation to enable us to show performance improvements for the actual PA device using our combined PAPR reduction and digital PD.

2. SYSTEM MODEL

The system includes transmitter, channel and receiver, as shown in Figure 1. We investigate two OFDM transmission schemes within this system when evaluating improvements. These two schemes differ in the power and placement of the pilot sub-carriers. The first scheme has uniformly spaced constant power (USCP) pilots; the second optimizes the placement and power (OPAP) of the pilots to minimize the MSE between the transmitted symbol and the receive-side estimate of the transmit symbol. Both OFDM schemes were introduced in [11] as joint synchronous pilot sequence (JSPS) OFDM, while a technique to optimize pilot placement and power was shown in [16]. Since the USCP OFDM and OPAP OFDM differ only in the pilot placement and power, both should have roughly the same PAPR statistics. Consequently, we anticipate that the transmit spectral improvements will be roughly equivalent. However, we do expect that the OPAP OFDM system will perform better at the receiver because of improved channel estimation performance.

As shown in Figure 1, we include a comprehensive communications model of our waveform so that simulation results come as close to implementation as possible. Our model includes all signal processing steps needed to transmit and receive the signal over an RF channel. The transmit side of the model includes all transmit filtering for up sampling and pulse shaping. The waveform has the capability to reduce PA distortion using two different methods. These processes are PAPR reduction [11] and PA PD, as described in [15]. Finally, we create and include a PA model of the state of the art PA hardware. Figure 2 portrays the lab data

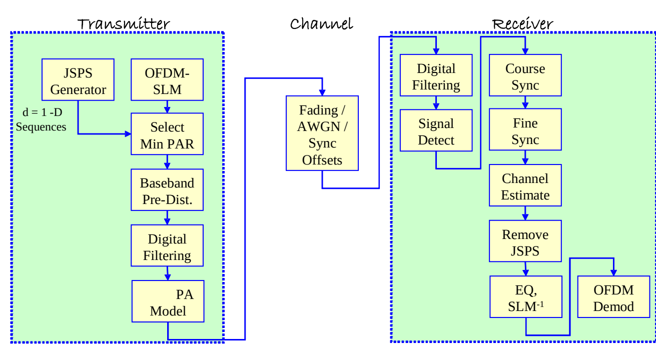

Figure 1: JSPS-OFDM System Model

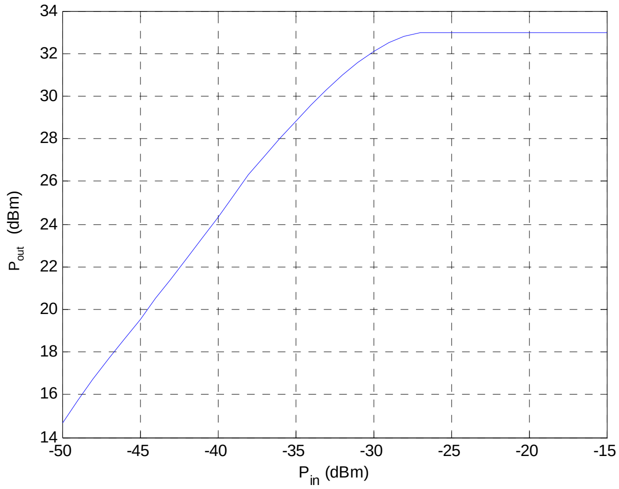

Figure 2: Lab Measurement of a state of the art PA

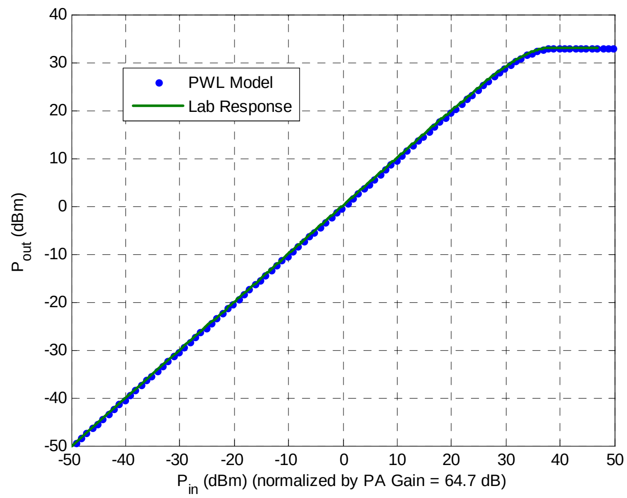

Figure 3: Lab Response and Piece-wise Linear Model

and Figure 3 illustrates the piecewise linear model of a state of the art PA (normalized to unity gain) used within the system. Within our model, we consider both AWGN and fading channels. The transmission structure, PAPR reduction technique and digital PD method will be outlined in Section 3.

Our model enables us to invoke either PAPR reduction and/or digital PD. The PAPR reduction is performed during the synthesis of the JSPS OFDM waveform, either with the OPAP or USCP pilot scheme. The PAPR reduction scheme is considered to be a selected mapping (SLM) scheme, but it is not the standard scheme as described in [5]. As detailed in [11], our scheme involves a complex optimization between the pilot subcarriers and synchronization subcarriers. In the JSPS waveform design, even though the pilots are considered as part of the overall synchronization sequence, used for coarse timing and frequency synchronization, their primary design objective is for channel estimation and fine synchronization. It is seen in [11] that higher power dedicated to pilots will improve channel estimation performance, but at the expense of lower coarse synchronization performance. The ratio of the power in the pilot subcarriers to the power in the synchronization subcarriers is an important design parameter ensuring adequate channel estimation / fine synchronization performance while still providing adequate coarse synchronization performance (note only pilot information occupies the pilot subcarrier frequency bins, while both data and synchronization information reside in what is normally denoted as the data subcarrier frequency bins). In addition, the more total power dedicated to the JSPS part of the total OFDM signal power provides larger PAPR reductions, but at the expense of lower data information signal power. Evaluation of these tradeoffs can be found in [11].

A major factor in considering which method of digital PD to utilize is the tradeoff between algorithmic complexity and performance. Ideally, the system designer chooses the algorithm which provides the best waveform linearity while meeting spectral mask requirements, but with minimal complexity. However, frequently the algorithm that meets performance requirements is not the one with lowest processing complexity. As referenced earlier in Figure 3, we showed the PWL model of a state of the art PA; clearly this typical PWL could require an excessive number of table entries for a LUT implementation. For a small form factor software defined radio (SDR), it is critical that low complexity implementations be considered. Consequently, later in Section 4 we will also describe a lower complexity version of the digital PD method we utilize in this work, largely based on the formulation found in [15] which proposes the use of simplicial canonical piecewise linear (SCPWL) functions. For the waveform considered here, we found very little memory effects from the chosen state of the art PA device and thus SCPWL techniques are a good match.

3. OFDM SYSTEM DETAILS

The JSPS OFDM waveform contains data and pilot subcarriers as usual. However, this waveform does not include a separate preamble for synchronization. Instead, the synchronization is embedded (superimposed) within the pilot and data sub-carriers. Figure 4 illustrates the details of the JSPS OFDM waveform but without the digital PD, transmit filtering and PA in the transmitter as was shown in Figure 1. We include only the PAPR reduction part in this discussion to simplify the explanation of the operation of the JSPS OFDM portion of the model shown in Figure 1.

The frequency-domain transmit data X_k is added to the synchronization data, S_k, as follows:

$$Y_k^{(d)} = \sqrt{\rho}\, S_k^{(d)} + \sqrt{1-\rho}\, X_k e^{j\varphi_k^{(d)}}, \tag{1}$$

where d and associated $\varphi^{(d)}$ represent one of D sequences and phase rotations designed to reduce the overall PAR, as described in [11]. Furthermore, ρ represents a partition of energy assigned to the JSPS synchronization-pilot sequence, which is embedded within the data.

Subsequently, the transmit sequence in the time domain is

$$y^{(d)}[n] = IDFT\{Y_k^{(d)}\} . \tag{2}$$

Let

$$\tilde{d} = \min_{d \in \{1,2,...,D\}} PAR\{y^{(d)}[n]\} , \tag{3}$$

then $y^{(\tilde{d})}[n]$ is chosen for transmission to minimize the overall PAR.

The received signal, $z^{(\tilde{d})}[n]$, contains time offset (TO), carrier frequency offset (CFO), and PA system described by

$$z^{(\tilde{d})}[n] = (f_{\beta}(y^{(\tilde{d})}[n-n_0]) * h[n])e^{-j2\pi\varepsilon/N} + \eta[n] , \tag{4}$$

where ε is the CFO, n_0 is the TO, $f_\beta(\cdot)$ is the PA system characteristic, $\eta[n]$ is the receiver AWGN, $h[n]$ is the multi-path Rayleigh fading channel and N is the total number of sub- carriers, where $N = 256$ for this work.

Since the receiver has no knowledge of $\tilde{d}$, the following calculations are performed to estimate $\tilde{d}$, along with the CFO and the TO. We start with the conjugate correlation defined as

$$CC\{a[n],b[n]\} = (\sum_{n=0}^{N/2-1} a^*[n]b[n-u]) \cdot (\sum_{n=N/2}^{N-1} a^*[n]b[n-u])^* , \tag{5}$$

to form

$$r^{(d)}[u] = CC\{s^{(d)}[n], z^{(\tilde{d})}[n-u]\} . \tag{6}$$

Then,

$$\hat{\tilde{d}} = \arg\max_{d} |r^{(d)}[u]| , \tag{7}$$

$$\hat{n}_0 = \arg\max_{u} |r^{(\hat{\tilde{d}})}[u]| , \text{ and} \tag{8}$$

$$\hat{\varepsilon} = \arg(r^{(\hat{\tilde{d}})}[\hat{n}_0]) . \tag{9}$$

After transforming the received signal back to the frequency domain, the receiver obtains

$$W_k^{(\tilde{d})} = IDFT\{z^{(\tilde{d})}[n+\hat{n}_0]e^{j2\pi n\hat{\varepsilon}/N}\} . \tag{10}$$

The estimate of the channel is obtained by

$$\hat{H}_k = \frac{W_k^{(\tilde{d})}}{S_k^{(\hat{\tilde{d}})}} , \tag{11}$$

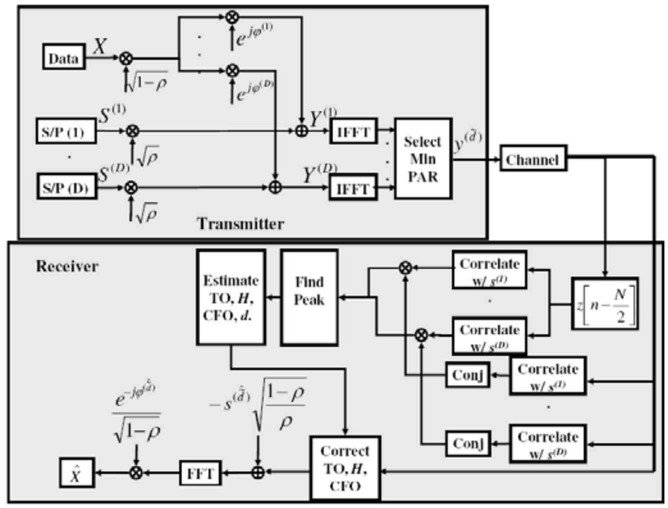

Figure 4: Further Iterative Decoding Detail

where k is contained within the set of pilot sub-carriers. As mentioned above, we consider both AWGN and fading channels. We can then perform linear interpolation to calculate $\hat{H}_k$ for the data sub-carriers as well. In this work we use a least squares estimator to estimate the channel. The estimate of the transmitted sequence X is then obtained as

$$\hat{X}_k = \frac{e^{-j\varphi_k^{(\hat{\tilde{d}})}}}{\sqrt{1-\rho}} (\frac{W_k^{(\tilde{d})}}{\hat{H}_k} - \sqrt{\rho} S_k^{(\hat{\tilde{d}})}) , \tag{12}$$

where k is contained within the set of data sub-carriers.

4. DIGITAL PREDISTORTION

The efficiency of a small hand-held radio transmitter with high power (1 Watt or greater) is dominated by the efficiency of the transmitter PA [17]. Consequently, it is imperative that the PA power added efficiency is maximized; in general this implies that the PA should be operated as close to saturation as possible. Thus, in order to achieve maximum efficiency from the PA, it is desired to run the PA at low input (or output) power backoff levels.

After reducing the PAPR as described using JSPS OFDM from (2) in Section 3, the transmit signal will still have a non-constant modulus (i.e., signal peaks will be distorted by the non-linear region of the PA). Consequently the transmitted spectrum could still exhibit significant distortion and spectral regrowth without further mitigation downstream in the transmitter. Pre-distortion of the signal in (2) will reduce the final distortion at the PA output of the transmitter and thus enable operation as close to the compression region as possible. Although the details of the SCPWL can be found in [15] for a typical baseband modulation signal, we summarize it’s application to JSPS OFDM here.

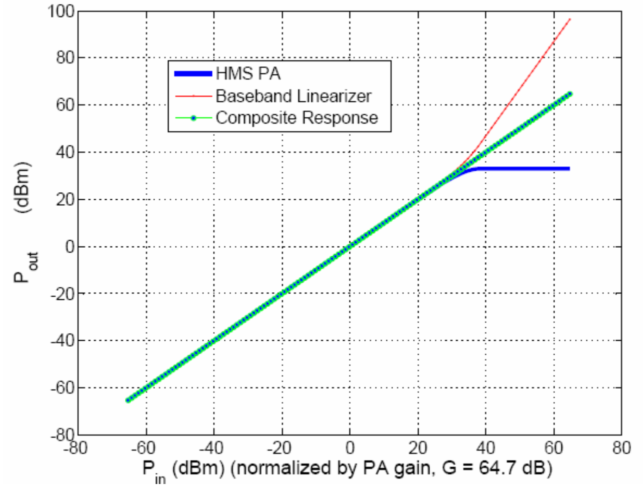

Figure 5: Actual PA, ideal PD and combined response.

We can express lowest PAPR signal in (2) in polar form as $y^{(\tilde{d})} = y_M e^{jy_\phi}$ such that

$$y_M = \left| y^{(\tilde{d})} \right| \text{ and } y_\phi = \angle y^{(\tilde{d})} . \tag{13}$$

The SCPWL function for a real valued input, x, can be written as

$$f_\beta(x) = a_0 + \sum_{k=1}^{P-1} a_k \lambda_k(x) = \mathbf{a}^T \Lambda_\beta(x), \tag{14}$$

where $\Lambda_\beta(x) = [1, \lambda_1(x), \ldots, \lambda_{P-1}(x)]^T$ is the basis function vector and $\mathbf{a} = [a_0, \ldots, a_{P-1}]^T$ is the SCPWL coefficient vector. The piecewise polynomial is broken in to predefined segments characterized by breakpoints $\boldsymbol{\beta} = [\beta_1, \ldots, \beta_P]^T$. The segments can be designed to optimally fit the non-linear function $f_\beta(x)$ of the PA system, with P breakpoints. The PA system is then modeled by the SCPWL function $f_\beta(x)$ defined by a set of basis functions from $\Lambda_\beta(x)$ and coefficient vector $\mathbf{a}$. The SCPWL function can be used to model static non-linearities for both AM/AM and AM/PM PA behavioral characteristics. (14) is used to model the PA function as measured in Figure 2. Figure 5 shows the ideal digital SCPWL PD and combined response with the PA characteristic. It is not possible for the PA to amplify the signal more than the saturation power in the compression region. Thus, once the PA reaches maximum output power capability, the digital PD has no effect and can no longer overcome non-linearity in this region, as shown in Figure 6. Consequently, the usable PD range for this PA, in terms of output power, is approximately 10 dB from about 23 dBm to 33 dBm.

5. EXPERIMENTAL RESULTS

The two metrics that are used to evaluate the performance improvement that PAPR reduction and PD provide are transmitted spectral regrowth and the received data constellation variance. In this work the OFDM waveform we

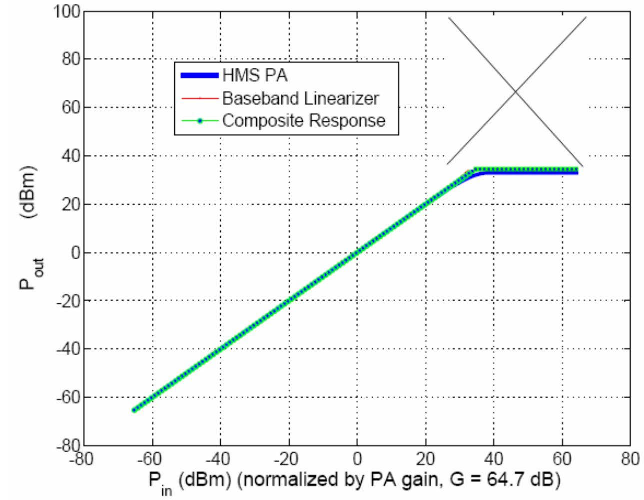

Figure 6: Actual PA, practical PD and combined response.

utilize consists of 256 total carriers, of which 176 are used for data transmission and 16 are used as pilots. The baseband sample rate for the simulations is 1 Msps with a guard interval of 15 samples.

Figures 7 and 8 represent the transmitted spectrum under 4 different transmission modes for 9 and 6 dB IBO, respectively. “PA-No LIN” represents the mode when the PA is used, but without PD or PAPR reduction, “PA-LIN” is the same but with PD and “PA-LIN-JSPS” represents PD and PAPR reduction, but with two different methods of choosing the best optimal transmit signal. The two choices are “minDIFF” and “minPAR.” “minDIFF” chooses the transmit signal, out of D choices, that minimizes the distortion between the ideal (non-clipped) signal and one that is clipped with a soft clipper, while “minPAR” chooses the tranmsit signal with the minimum PAR before any PA clipping. The best overall combined effect occurs when PD (PA-LIN) is utilized with “minPAR” PAPR reduction. The spectral regrowth reduction is approximately 15 dB and 10

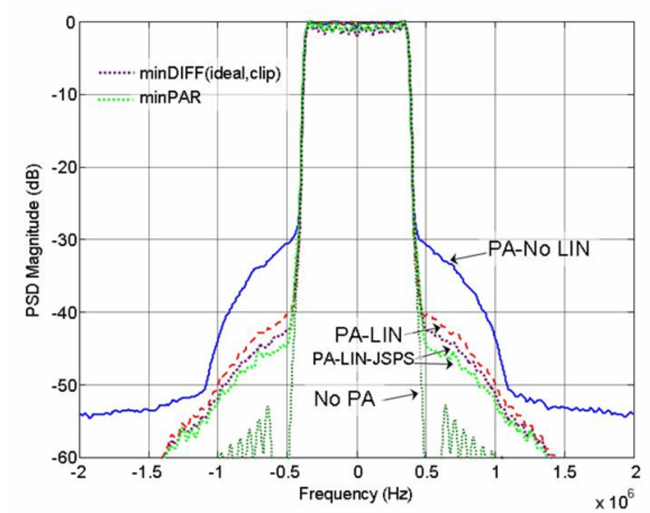

Figure 7: Transmit spectrum for 9 dB IBO.

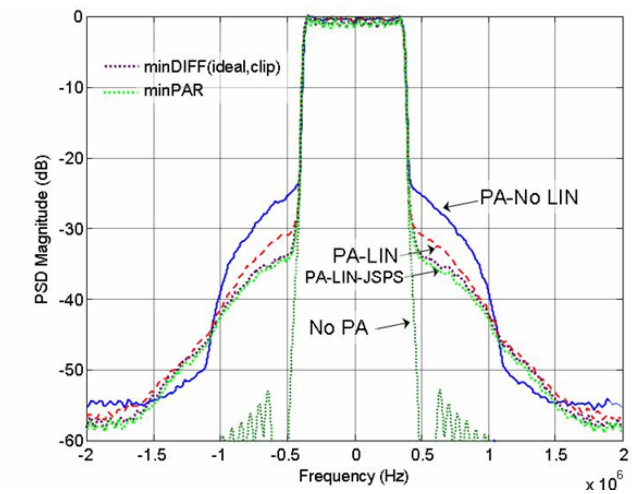

Figure 8: Transmit spectrum for 6 dB IBO.

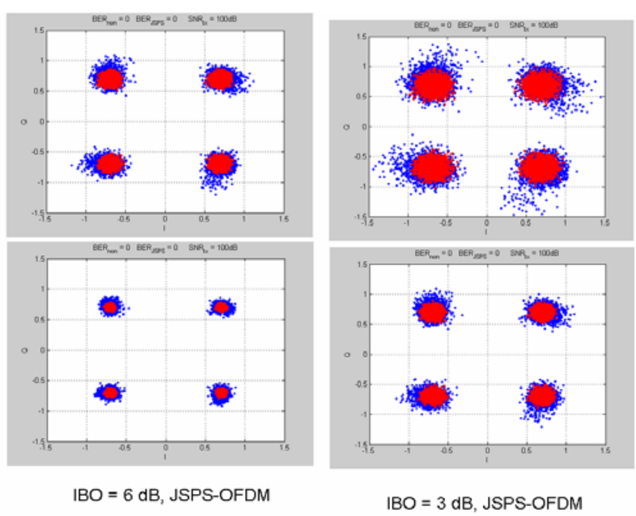

Figure 9: Receiver constellations, top: no PD or PAPR reduction, bottom: combined PD and PAPR reduction.

dB at IBO of 9 dB and 6 dB, respectively. Figure 9 shows the received constellations before (top) and after (bottom) PD and PAPR reduction for 6 dB and 3 dB IBO, respectively. The red and blue constellations represent the OPAP and USCP JSPS OFDM waveforms, respectively. It is clear that the OPAP pilot scheme provides reduced variance compared to USCP, amounting to about 1-2 dB improvement in the PA and AWGN channel. Combined PD and PAPR reduction provides around a 3-4 dB reduction in the received constellation variance.

6. CONCLUSION*

In this work, we proposed using peak-to-average power ratio (PAPR) reduction and digital pre-distortion (PD) to improve OFDM transmit spectral regrowth and the received data constellation variance. We applied these proposed performance improvements to a JSPS OFDM waveform using two difference pilot designs. At reasonable operating regions of the transmit PA, we found a 10 to 15 dB reduction in spectral regrowth and a 3-4 dB reduction in the received constellation variance, while the optimized pilot design (OPAP) provided reduced variance compared to USCP.

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