# Power Backoff Reduction for Generalized Multicarrier Waveforms

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## ABSTRACT

*Amplification of generalized multicarrier (GMC) signals by high power amplifiers (HPA) before transmission can result in undesirable out of band spectral components, necessitating power backoff and low HPA efficiency. We describe and evaluate several peak to average power ratio (PAPR) reduction techniques which apply to GMC signals, including OFDM and serial modulation. Required power backoff is shown to depend on the type of signal transmitted, the specific HPA nonlinearity characteristic, and the spectrum mask which is imposed to limit adjacent channel interference. PAPR reduction and HPA linearization techniques are shown to be very effective when combined.*

## 1. INTRODUCTION

High power amplifiers (HPA) used in radio transmitters have nonlinear characteristics which can cause significant distortion to signals whose instantaneous power fluctuations come too close to the HPA's output saturation power. Even small amounts of nonlinear distortion can cause undesirable spectral regrowth, which can interfere with signals in adjacent frequency channels. Regulatory agencies impose spectral masks on transmitted spectra to limit worst-case adjacent channel interference. Larger amounts of nonlinear distortion also cause significant nonlinear in-band self-interference, which results in increased received bit error rate. Normally, HPA's are operated with a certain "power backoff" – which can be defined as the ratio of maximum saturation output power to average output power. Increasing the backoff reduces the nonlinear distortion, but causes lower HPA efficiency and higher overall power consumption and battery drain. It also calls for a more expensive HPA, with a higher maximum output power rating to produce a given average output power. The HPA is generally one of the most significant cost components of user terminals, and the relationship of HPA cost to maximum power rating is an important technology issue. However the cost can rise sharply with the output power rating, and is affected not only by the HPA device itself, but can also be affected by thermodynamics: provision of heat sinks, fans, etc.

Minimizing power backoff is thus desirable, without sacrificing BER performance or spectral efficiency, especially for cost- and power-sensitive user terminals. Two main approaches are pursued, which can be applied singly or in combination: (1) direct HPA predistortion to compensate for the HPA distortion; (2) peak to average power ratio (PAPR) reduction to reduce the dynamic range of the transmitted signal before it is applied to the HPA. The requirements and methods are strongly dependent on the modulation and multiplexing scheme. For example, multicarrier, or parallel modulation and multiplexing schemes, such as OFDM and MC-CDMA, have inherently higher PAPR value than single carrier, or serial schemes, and hence the PAPR reduction schemes have been extensively studied for OFDM and other multicarrier signals. In this paper we present recent findings on PAPR reduction for a more general class of waveforms – *generalized multicarrier.*

## 2. PAPR FOR OFDM AND OTHER GENERALIZED MULTICARRIER SIGNALS

A block OFDM signal, transmitting coded data symbols $\{A_m, m=0,1,..M\}$, is normally generated as the inverse discrete Fourier transform (DFT) of the data symbol sequence. The resulting *OFDM symbol*, sampled at $N \geq M$ times per block, is expressed as

$$s(n) = \frac{1}{\sqrt{M}} \sum_{m=0}^{M-1} A_m \exp(j\frac{2\pi mn}{N}), \qquad n = 0,1,...N-1. \qquad (1)$$

Any sample $s(n)$ is a linear combination of $M$ data symbols, equally weighted in magnitude. Therefore its maximum possible magnitude is at least $M$ times the average data symbol magnitude. This ratio could be the basis for the peak to average power ratio (PAPR) definition, but it is not very useful, since for large $N$ the peak magnitude is seldom achieved. A statistical definition of PAPR is instead commonly used: the ratio of the maximum instantaneous power in a given block to the average signal power. This and other measures reflecting signal magnitude variation will be discussed later.

A more general form of OFDM signal format, called *generalized multicarrier* (GMC) [WG00],[FK05] is formed by performing a matrix transformation on the vector $\mathbf{a}$ of $M$ data symbols before applying (1). The transmitted signal can be expressed as a $N$-dimensional vector

$$\mathbf{s} = \mathbf{F}^*\mathbf{Ma} \qquad (2)$$

where $\mathbf{M}$ is a $N$ by $M$ matrix and $\mathbf{F}^*$ is the $N$ by $N$ inverse DFT matrix. Signal types such as multicarrier code division multiple access (MC-CDMA) and interleaved frequency division multiple access (IFDMA) can be generated in this way, by the appropriate choice of $\mathbf{M}$. Choosing $\mathbf{M}$ as an identity matrix gives OFDM. Inserting rows of zeroes in the identity matrix gives orthogonal frequency division multiple access (OFDMA), in which data-bearing subcarriers are selected based on diversity or traffic considerations. A version of GMC that is of interest in this paper is *DFT-precoded OFDM*, in which $\mathbf{M}$ contains a DFT matrix; i.e.

$$\mathbf{M} = \begin{bmatrix} \mathbf{F} \\ \mathbf{0} \end{bmatrix} \qquad (3)$$

where $\mathbf{F}$ is a $M$ by $M$ DFT matrix, and $\mathbf{0}$ is a $(N\text{-}M)$ by $M$ matrix of zeroes. Combining (3) and (2) yields the expression for the sampled waveform

$$s(n) = \sum_{m=0}^{M-1} a_m g(n - m\frac{N}{M}) \quad n = 0,1,...N-1 \qquad (4)$$

where $$g(n) = \frac{1}{M} e^{j\frac{\pi}{N}(M-1)n} \frac{\sin\frac{\pi M}{N}n}{\sin\frac{\pi}{N}n} \qquad (5)$$

This describes samples of a *serial modulated* (SM), or *single carrier* (SC) waveform, in which data symbols are transmitted serially, at intervals of $N/M$ samples by pulse amplitude modulating a pulse waveform $g(t)$. $g(t)$ is a circularly-shifted, sampled, time-limited to $N$ samples, version of a pulse with zero excess bandwidth. Its envelope decays as $n^{-1}$. Thus the magnitude of each sample $s(n)$ is mainly determined by a weighted sum of a small number (much less than $M$) of adjacent data symbols, and so, as with any SM waveform, its dynamic range will be much less than that of the equivalent OFDM waveform. The amplitude range of $s(n)$ can be further reduced, at the expense of increasing the signal bandwidth, by replacing $g(t)$ by a raised cosine or other pulse with excess bandwidth.

Another variant of DFT-precoded OFDM, with similar low-PAPR properties, is interleaved frequency division multiple access (IFDMA), in which $L$ rows of zeroes are inserted after every row of $\mathbf{F}$ in (3) [DFL+04]. The signal spectrum then consists of $M$ DFT-modulated subcarriers at intervals of $L$. The pulse $g(n)$ can then be shown to be that of (5), but with $n$ replaced by $Ln$. IFDMA has the advantage over contiguous-spectrum signals of extra frequency diversity since its spectrum is spread over a wider band. Another recently proposed variation is block IFDMA (B-IFDMA), in which subcarriers are grouped in small blocks, well separated from other blocks [SFF+07]. In contrast to IFDMA, B-IFDMA does *not* result in a pure serial modulation waveform, but as shown later it still has good PAPR and power backoff properties.

PAPR is a commonly-used measure of the range of a signal's amplitude. It is a reasonably good *qualitative* measure; signals with low PAPR generally require less power backoff and exhibit less performance sensitivity when amplified by a nonlinear HPA, than do signals with high PAPR. However PAPR is determined by the single largest-amplitude sample in a block of $N$ samples, and therefore is not a good *quantitative* measure of nonlinearity sensitivity.

Somewhat more informative is the complementary cumulative distribution (CCDF) function of the signal amplitude measured over many samples. Figure 1 illustrates CCDFs of QPSK serial modulated and OFDMA signals generated by (a) the frequency domain method of equations (3)-(5), with zero excess bandwidth and $\alpha$=5.5% time domain widowing, and (b) the traditional time domain method, with $\alpha$=25% excess bandwidth square root raised cosine filtering of the time domain waveform. The lower amplitude range of the serial modulated (or DFT-precoded OFDM) signal is evident. It is also evident that excess bandwidth (25% versus 0%) reduces the amplitude range of the serial modulation signal, because of lower $g(n)$ sidelobes, while having no effect on the OFDM signal's amplitude range.

However, the CCDF does not provide quantitative information about sensitivity to specific HPA nonlinearities. Such information is available from the simulation of nonlinear amplification of waveforms, using realistic power amplifier models and measuring output power spectra and signal to distortion ratios. A Rapp model [Rap91] (see Figure 2), with a parameter $p$=2, is a fairly good approximation to the amplitude-to-amplitude conversion characteristic of a typical solid state power amplifier. The ratio of output to input amplitude in this model with parameter $p$ is given by

$$\left|\frac{V_{out}}{V_{in}}\right| = \frac{1}{\left[1+\left|\frac{V_{in}}{V_{sat}}\right|^{2p}\right]^{1/2p}} \qquad (6)$$

where $V_{sat}$ is the saturated output level of the amplifier[1]. With $p$=10 or higher, the characteristic approaches that of an ideal linear clipper.

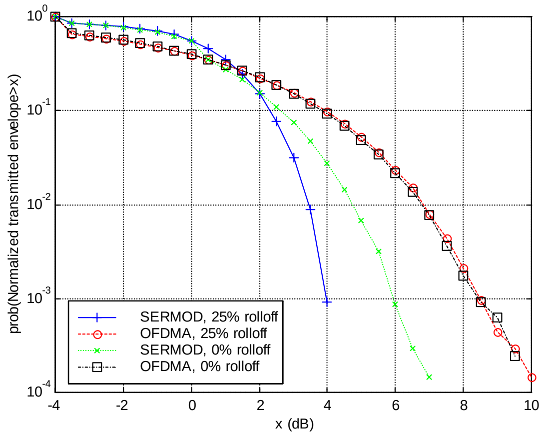



Figure 1 Distribution of instantaneous power for comparable OFDMA and SM waveforms with 0% and 25% rolloff.

Examples of spectral regrowth due to a $p$=2 nonlinearity for the OFDM and serial modulated QPSK signals of Figure 1 are shown in Figure 3(a) and 3(b). Figure 3(a) shows that for the frequency domain-generated, 0% excess bandwidth (also called rolloff) signals, serial modulation and OFDM require 8 dB and 10 dB backoff, respectively, for comparable maximum spectrum sidelobe levels of about -40 dB. The backoff for serial modulation is further decreased to about 7.3 dB for the time domain generated signals with 25% rolloff. It is found that increasing the excess bandwidth from near zero to 12.5% yields the greatest decrease in backoff for serial modulation; beyond 12.5%, there is little further reduction in backoff, and in fact the signal bandwidth is widened by the increased rolloff.

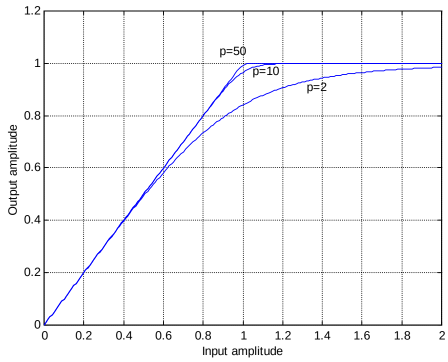
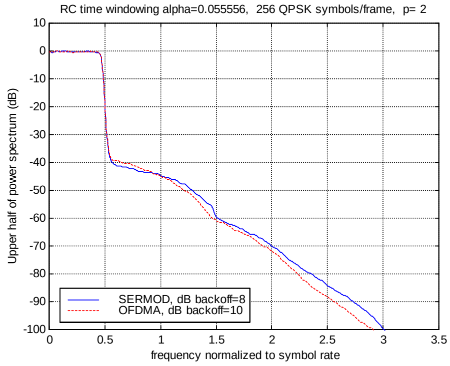



Figure 2 Rapp model of HPA nonlinearity

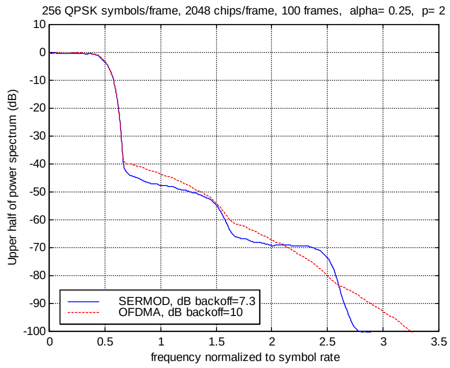
The required power backoff is significantly reduced by up to 2.5 to 3dB for a HPA with Rapp parameter $p$=10, that approximates an ideal linear clipper, as shown in Figure 4 for the 0% excess bandwidth case. Increasing the rolloff factor to 25% for $p$=10 reduces the backoff by a further 2.5 dB for SM, but there is little further decrease beyond that rolloff value. Actually, the backoff required for OFDM increases slightly as the rolloff increases beyond 25%.
At these levels of spectral regrowth (which conform to typical spectral mask requirements), the received in-band signal-to-nonlinear distortion ratios are quite small: on the order of 35 to 40 dB. In gen-

[1] In this formula, the amplifier gain is normalized to unity for notational convenience.

eral, we find that the spectral regrowth allowed by typical spectral masks is the dominating criterion for HPA nonlinearity effects. In-band nonlinear distortion of the received signal is negligible at backoff values that start to impinge on typical spectral masks.




(a)




(b)

Figure 3. Power spectrum at output of a $p$=2 Rapp nonlinearity for QPSK OFDM and SM signals with (a) 0% and (b) 25% excess bandwidth

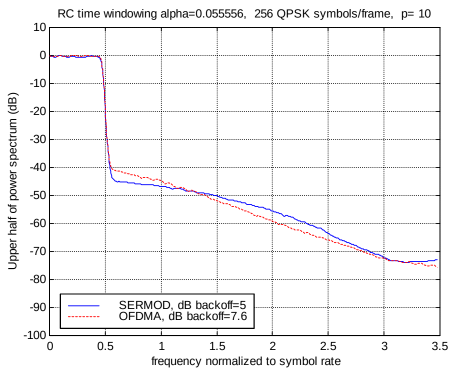



Figure 4. Power spectrum at output of a $p$=10 Rapp nonlinearity for QPSK OFDM and SM signals with 0% excess bandwidth

## 3. SOME PAPR REDUCTION TECHNIQUES

Methods for PAPR reduction of OFDM signals include nonlinear block error correction coding [JW96], selective mapping (SLM) [CS00], partial transmit sequences [CS00], [MH97], and reference signal subtraction [LR99]. All of these methods require significant transmitter signal processing complexity and also require the transmission of extra overhead.

OFDM signals may also be clipped to remove power peaks, followed by filtering to suppress out of band spectral re-growth caused by the nonlinear clipping operation. (see [DG04] and references therein). This approach has the virtue that no extra processing or side information is necessary for reception, but it can cause a slight degradation in bit error rate due to the clipping-caused nonlinear distortion on the signal.

It is perhaps not so well appreciated that many of these techniques can also be applied to other GMC signals, such as serial modulation. Even clipping and filtering can be applied to serial modulation. Figure 5 shows spectral regrowth at the output of a HPA whose 0% rolloff input has undergone four iterations of clipping and filtering, similar to that described in [DG04]. The clipping level for the OFDMA signal is twice its standard deviation, while that for the serial modulated signal is 1.5 times its standard deviation. The clipping operation introduces some nonlinear distortion in the received signal, which increases with the number of iterations of clipping and filtering. However with 4 iterations in this example, each waveform's mean square distortion at the receiver output is more than 25 dB below the desired signal output level. In Figure 5, the HPA is modelled as a nearly ideal linear clipper, with Rapp parameter $p$=10. Also shown in the figure is a scaled ETSI 3GPP spectral mask. Comparison with Figure 4 shows a decrease in backoff of at least 1 dB resulting from the clipping and filtering for both SM and OFDM. A similar trial with a $p$=2 HPA resulted in no backoff improvement. Again we see that HPA linearization is complimentary to a PAPR reduction method.

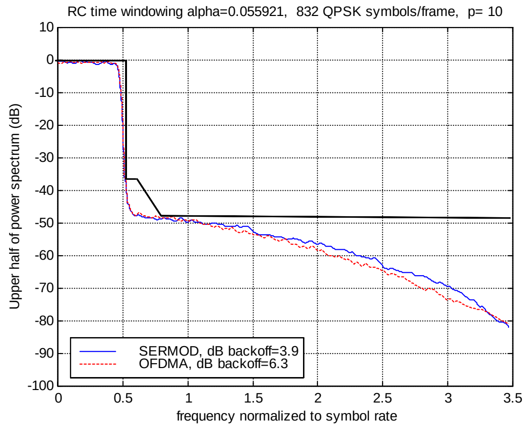



Figure 5. Output power spectra of iteratively clipped and filtered signals passed through a $p$=10 Rapp nonlinearity. ETSI 3GPP spectral mask is also shown.

Another PAPR-reduction method previously proposed for OFDM is Selective Mapping (SLM) [MH97]. This method is based on generating $N_s$ different transformed blocks for each given block of data. Then it transmits the one with the lowest PAPR and some side information to the receiver about the identity of the transform of the block. In the conventional SLM method, to generate independent blocks of data, each block is multiplied symbol-by-symbol, before the IFFT operation, by one of the pseudo-random but fixed set of vectors $\mathbf{r_i}$ whose elements are complex numbers with the amplitude equal to one and a random phase uniformly distributed between [0,2π].

A modified version of the SLM algorithm for SM is suggested in [SF05]. In SM, high peaks are generated after filtering, when there are large magnitude points of the constellation near each other in the data sequence. Consequently, the number of large peaks in a SM block is greater than that of OFDM. This motivates a modification of the SLM selection criterion from PAPR to a least squares-based rule. A further modification is the use of block permutations instead of phase modulations. The resulting modified form of SLM applied to SM is most effective for lowering the required backoff for $p$=10 [SF05]. This means that SLM, like other PAPR-reduction methods, is most effective when used with a HPA that approximates an ideal linear clipper, or whose input-output characteristic is compensated by an adaptive pre-distortion scheme, such as that of [Wes05]. [SF06] describes a variation of this PAPR reduction method applied to MC-CDMA and serial CDMA.

## 4. GMC SIGNALS WITH NON-CONTIGUOUS DATA SPECTRA

For the purpose of channel estimation for frequency domain equalizer adaptation, pilot training signals are multiplexed with data signals. If they are time-multiplexed via separate short training blocks, there is no implication for PAPR or power backoff, as long as the training signals have uniform amplitude, such as Chu sequences [Chu72]. However pilots frequency-multiplexed with data can affect PAPR properties of the resulting composite signal. A common form of frequency multiplexed pilots are inserted with a *frequency expanding technique* (FET). In this technique, rows of zeroes are periodically inserted in the **F** matrix in equation (3) in the case of DFT-precoded OFDM, or in the identity matrix in **M** in the case of OFDM. Thus pilot tones appear at uniformly spaced frequencies in the transmitted spectrum, surrounded by data-carrying tones. The pilot tones can be chosen to be DFT components of a Chu sequence, so that the power spectrum and amplitude samples of the pilot waveform are uniform [LFD+06]. The FET pilot sequence in the frequency domain is the $L$-point DFT of the Chu sequence. Since the pilot subcarriers are at regular intervals, the added pilot waveform is equivalent to a low-PAPR IFDMA waveform.

For OFDM, there is little or no effect on PAPR properties, since pilot tones resemble data tones. However when FET pilots are applied to DFT-precoded OFDM, the resulting time domain sampled data waveform (not including the pilot waveform) can be shown to be [LFD+06]

$$s(n)=\sum_{m=0}^{M-1} a_m\, g_1\!\left(n-m\frac{N}{M}\right) g_2\!\left(n-m\frac{NK}{(K+1)M}\right)$$

where $K$ is the inter-pilot spacing, and

$$g_1(n)=\frac{1}{\sqrt{M}}\, e^{j\frac{\pi}{N}(K-1)n}\,\frac{\sin\left(\frac{\pi K}{N}n\right)}{\sin\left(\frac{\pi}{N}n\right)}$$

and $$g_2(n)=\frac{1}{\sqrt{M}}\, e^{j\frac{\pi}{N}(K+1)\left(\frac{M}{K}-1\right)n}\,\frac{\sin\left(\frac{\pi(K+1)M}{NK}n\right)}{\sin\left(\frac{\pi(K+1)}{N}n\right)}.$$

This is no longer a pure serial modulated waveform, and so it can be expected that its amplitude range properties will be worse than that of the SM waveform of equation (5). Furthermore the pilot waveform is added to it.

Figure 6 shows double-sided QPSK DFT-precoded (SM) and OFDM spectra at the output of a Rapp $p$=2 nonlinearity, along with a spectral mask that has been proposed for WINNER wireless systems [D2.5]. The signals are of the same type as those of Figure 3(a), but have FET pilots added to them at every fourth subcarrier. The OFDM spectrum and backoff to satisfy the mask are nearly identical to that of Figure 3(a), but the serial modulated signal with FET pilots requires about 1 dB higher backoff, although it is still 1 dB less than that of the OFDM signal. Typical pilot arrangements will place pilots in only a fraction of the transmitted blocks; e.g. in 2 blocks out of 12 as in [LFD+06]. Thus only a fraction of transmitted SM blocks need the slight extra backoff associated with FET pilots. For those blocks, the pilot level can be boosted slightly and the data power can be decreased, the only effect being a fraction of a dB loss in average data signal SNR [ADF+07]. In Figure 6, the pilot power has been boosted by 1 dB for the SM signal, and the resulting SNR loss to data if 1/6 of transmitted blocks have pilots is 0.2 dB.

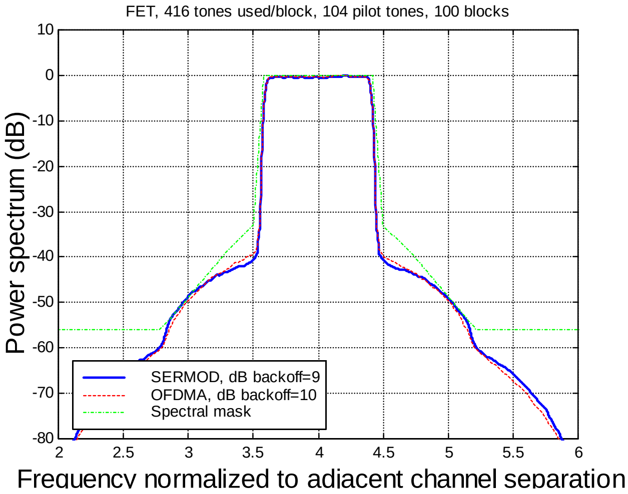



Figure 6. Power spectra for $p$=2 Rapp model nonlinearity for QPSK serial modulated and OFDM signals, with FET pilot tone at every 4th subcarrier.

Figure 7 shows a spectral regrowth plot for B-IFDMA signals mentioned in Section 2, and further detailed in [SFF+07]. Even though the B-IFDMA waveform is not a pure SM waveform, its backoff is less than that of the OFDMA signal.

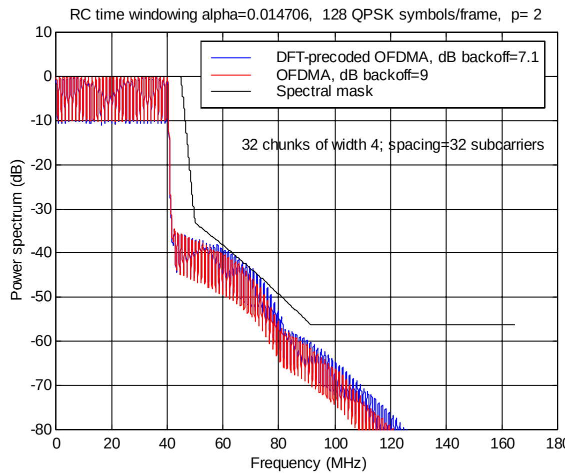



Figure 7 HPA output power spectra for OFDMA and DFT-precoded OFDMA (B-IFDMA), with block width=4 and with 40 MHz nominal bandwidth. HPA has Rapp model nonlinearity with parameter p=2.

[GEP06] proposed a method of reducing the PAPR for OFDM signal by selecting the pilot sequence from a number of possible orthogonal Walsh-Hadamard pilot sequences, such that the OFDM signal with pilots gives the lowest PAPR. The use of orthogonal pilot sequences facilitates blind detection of which pilot sequence has been sent, by the receiver, as described in [GEP06], so that no side information is necessary. [LFD07] extends this concept to DFT-precoded OFDM signals, using orthogonal cyclically-shifted Chu pilot sequences instead of Walsh-Hadamard sequences, and using either a PAPR selection rule as in [GEP06] or the SSE selection rule of [SF05].

Figure 8 shows power spectra from the output of a $p$=10 Rapp nonlinearity, using this cyclically shifted Chu pilot sequence selection technique, with power backoff of 7 dB, for both DFT-precoded

OFDM and OFDM signals. The parameter $N_s$ is the number of Chu pilot sequences from which the PAPR-minimizing selection is made. Results for the SSE rule are similar [LFD07]. $N_s$=1 corresponds to conventional FET pilots with no PAPR reduction applied. Every fourth subcarrier is a pilot. Choosing from $N_s$=32 possible pilot sequences is seen to reduce sidelobe regrowth slightly for the serial modulation case, even showing improvement over the case of no pilots. The improvement for OFDM is more significant. Again however, the improvement is only significant for the linear clipper ($p$=10) HPA model; there is little improvement for $p$=2 [LFD07]. In [Wes07], this idea is carried further, by combining it with the SLM procedure: each possible orthogonal pilot sequence is combined with a different SLM mask sequence. The mask/pilot combination giving the least PAPR is chosen at the transmitter.

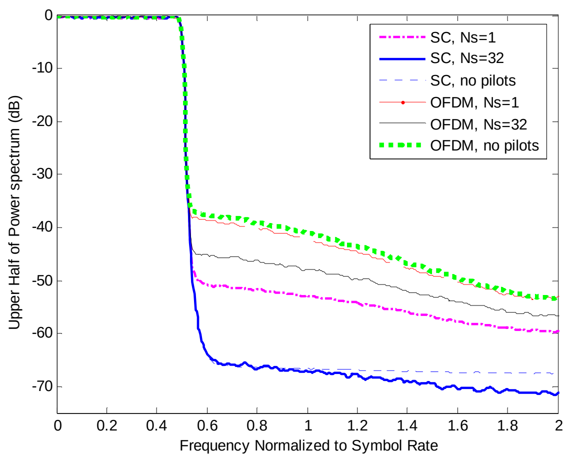



Figure 8. Power spectra of QPSK SM and OFDM signals with $M$=416 data symbols/block, 104 FET pilots formed from one of $N_s$ cyclically shifted Chu sequences chosen to minimize PAPR. Rapp parameter $p$=10. Backoff=7 dB.

## 5. SUMMARY AND CONCLUSIONS

We can summarize by listing the following conclusions:

- In general, transmitted signal power spectra must be confined within spectral masks. Some power backoff is necessary to keep spectral regrowth due to nonlinear HPAs within the mask limit.
- Most spectral masks are such that as long as they are not violated, in-band distortion and BER degradation due to HPA nonlinearity is negligible. This means that spectral regrowth is a more important criterion than BER when assessing nonlinear HPA effects.
- Required power backoff for a specific HPA nonlinearity model and spectrum mask is a better *quantitative* criterion than peak to average power ratio or its distribution.
- DFT-precoded OFDM has lower PAPR and lower backoff requirements than OFDM or OFDMA. It is equivalent to serial or single carrier modulation, if the transmitted subcarriers are contiguous or equally-spaced.
- DFT-precoded OFDM for non-contiguous and non-equally-spaced spectrum signals, such as B-IFDMA, also have lower backoff requirements than comparable OFDMA signals.
- Several PAPR reduction schemes that were previously found to be effective for OFDM are also effective for DFT-precoded OFDM.
- PAPR reduction schemes are most effective when combined with adaptive HPA pre-distortion, such as in [Wes05], which effectively makes the HPA nonlinear characteristic close to that of an ideal linear clipper.

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