Reducing the out of Band Radiation of OFDM Using an Extended Guard Interval

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Abstract—In this paper we investigate the spectrum, out of band radiation (OBR) and the use of extended guard interval (EGI) to reduce the out of band radiation of an OFDM signal when passing through different nonlinear devices. Spectra of the OFDM signal with different EGI lengths after passing through nonlinear devices are obtained through computer simulations. Mathematical expressions for the power spectral density of a conventional OFDM signal and an OFDM signal with different EGI lengths are also presented. Theoretical and simulated results are compared. Although the EGI reduces the OBR, this reduction is not significant in some cases. The effect of EGI on the OBR of an OFDM signal differs for different nonlinear devices. The EGI is also not capable of reducing the OBR caused by excessive clipping of the OFDM signal. Finally, it is also found that the length of the EGI does not have a considerable effect on the amount of OBR reduced when passing through a nonlinear device.

Index terms: OFDM, Out of band radiation, Non-linear devices.

I. INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is an attractive technique for the transmission of high-bit-rate data in a radio environment [1, 2]. It has recently gained great popularity due to its robustness in mitigating impairments such as inter symbol interference (ISI) due to multipath fading and impulsive noise in such systems. If a guard interval (GI) greater than length of the channel impulse response is chosen, the ISI is eliminated entirely. Another advantage of OFDM is its simple realization by means of efficient fast Fourier transform (FFT) algorithms. OFDM is already being investigated for new wireless standards and current OFDM applications include digital audio broadcasting, asynchronous digital subscriber lines, digital video broadcast- and wireless LANs. A recent addition to this list of applications is the IEEE 802.11 standard. However, any multicarrier signal with a large number of subchannels is burdened with a large peak-to-average power ratio (PAR). When passed through a nonlinear device, such as a transmitter power amplifier, the signal suffers significant power spectral spreading and in-band distortion. One solution to this problem is to use a highly linear amplifier with a sufficient input backoff (IBO), resulting in significant power efficiency penalty. Very high backoff demand by OFDM signals are a major disadvantage where peak signal power levels are constrained by design factors such as battery power in portable equipment. Another alternative to overcome this problem is to reduce the PAR of the OFDM signal before it is passing through the nonlinear device (amplifier).

Several alternative solutions have been proposed to reduce the PAR of an OFDM signal. Since high peaks occur with very low probability, the high peaks may be clipped when they occur [3]. However, this deliberate clipping of the signal causes significant distortion and increases the OBR and the BER. A model to analyze the effect of clipping of discrete multitone signal is presented in [4]. Model provides information on the reduction of the signal level, the total noise power due to clipping and spectral properties of the noise. Filtering after clipping can reduce the spectral splatter but may cause some peak re-growth. Clipping and filtering on the performance of OFDM has been investigated [5]. There are techniques capable of achieving significant PAR reductions in the expense of increased system complexity. Even with reduced PAR, OFDM signal needs significantly high IBO at the transmitter power amplifier. Therefore it is important to look at the spectrum of the OFDM signal, distortion caused by different nonlinear devices and the suitable means to reduce the high OBR.

Conventional OFDM signal itself possesses a high OBR due to sharp variations at the OFDM signal boundaries. This level of OBR increases when the OFDM signal passes through a nonlinear device. Studies of the spectrum and the OBR of OFDM signals can be found in the literature, with several OBR reduction methods. Symbol envelope shaping to reduce the OBR is the most popular scheme, which is used in magic WAND project [6] under the European union’s advanced communications technologies and services (ACTS). Oversampled inverse discrete Fourier transform (IDFT) output with a guard prefix is multiplied by a root-raised-cosine pulse-shaping window to achieve the expected performance. Although the reduction in spectrum splatter or OBR is achieved by this method, an increase in the bit error rate (BER) may occur due to shaping of the wanted signal.

An envelope-shaping and windowing schemes are proposed in [7] and [8]. In [7], signal envelope is multiplied with a weighting function composed of sum of Gaussian pulses. Different windowing functions are used for the same purpose in [8]. Both these techniques are used to remove the sharp transitions in the signal. The method of introducing EGI before windowing is analytically described in [7]. Instead of shaping the wanted signal, two extended portions are introduced at both ends of the OFDM signal and shaped using a raised cosine window. Effect of the use of EGI on the OBR of an OFDM signal is also analysed. Raised cosine windowing function is used. It is shown that the use of an EGI would not have any effect on the BER performance but reduces OBR significantly.

An another analytical result is presented in [9], where an expression is obtained for the spectrum of the OFDM signal after passing through a saturated high-power amplifier. Effect of hardware nonlinearities on OFDM transmissions is presented in many papers [10–12]. None of these papers considered common nonlinear devices into account and compared the spectrum and the OBR. No papers can be found which gives a proper account of the effect of EGI in the presence of common non-linearities.

This paper investigates the effect of EGI in the presence of different non-linearities. Next section derives the power spectral density of an OFDM signal with an EGI. Section 3 describes the different nonlinear devices used in the simulations. Section 4 presents the results. Finally, Section 5 concludes the paper.

II. SYSTEM DESCRIPTION

In OFDM, a block of N symbols, $X_n$, $n = 0, 1, \ldots, N - 1$, is formed with each symbol modulating one of a set of N subcarriers, $f_n$, $n = 0, 1, \ldots, N - 1$. The N subcarriers are chosen to be orthogonal, that is $f_n = n\Delta f$, where and $T$ is the original symbol period. The resulting signal can be expressed as

$$x(t) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} X_n e^{j2\pi f_n t}, 0 \leq t \leq T. \quad (1)$$
A cyclic prefix (called guard interval) is added to the resulting signal in order to avoid the intersymbol interference (ISI) which occur in multipath channels. At the receiver the guard interval is removed and only the time interval \([0, T]\) is evaluated. The guard interval usually a periodic extension of the symbol over the interval \([-TC_{GP}, 0]\), resulting in a symbol of length \([-TC_{GP}, T]\).

These time-domain samples in the equivalent complex valued low-pass domain are approximately Gaussian distributed, because of the statistical independence of carriers. Resulting high PAR is introduced. Now, the time interval \(T_s\) is overlapped in an interval of \(T_{GP}/2\). Power spectral density (PSD) of signal is then estimated after passing through a non-linear de-correlation function \(R\), resulting in a symbol of length \([-TC_{GP}, T]\).

The OFDM signal transmitted is then introduced. Now, the time interval \(T_s\) is overlapped in an interval of \(T_{GP}/2\). Power spectral density (PSD) of signal is then estimated after passing through a non-linear de-correlation function \(R\), resulting in a symbol of length \([-TC_{GP}, T]\).

The Fourier transform of the auto correlation function is equal to the power spectral density. This can be expressed as

\[
S(f) = \int R(\lambda) e^{j2\pi f \lambda} d\lambda
\]

where

\[
R(\lambda) = \frac{1}{T} \int_0^T w(t + \lambda) w^*(t) dt.
\]

We have

\[
S(f) = \frac{1}{T} \sum_{n=0}^{N-1} W^n [(f - n\Delta f)T]
\]

where \(W\) is the Fourier transform of the windowing function. The spectrum of an ordinary OFDM signal with a rectangular window can be expressed as

\[
S(f) = \frac{1}{T} \sum_{n=0}^{N-1} \left(\text{sinc} [(f - n\Delta f)T]\right)^2
\]

The raised cosine window function used to shape the OFDM signal can be expressed as follows

\[
w(t) = \begin{cases} 
0.5(1 + \cos \left(\pi \left(1 + \frac{t}{T_{cP}}\right)\right)) & 0 \leq t \leq \beta T_s \\
1 & \beta T_s \leq t \leq T_s \\
0.5(1 + \cos \left(\pi \left(t/T_s\right)\right)) & T_s \leq t \leq (1 + \beta) T_s 
\end{cases}
\]

where \(\beta = T_d/(2T_s)\) is the roll off factor. The spectrum of an OFDM signal with both GI and EGI multiplied by a raised cosine windowing function is given by

\[
S(f) = \sum_{n=0}^{N-1} \left\{\text{sinc} [(f - n\Delta f)T_s] \cos(\pi\beta(f - n\Delta f)/T_s)\right\}^2
\]

In this case the OBR decreases more rapidly with the roll off factor. However, increase in the EGI will reduce the efficiency [7] of the OFDM system which is defined as

\[
\eta = \frac{T}{T_{s}}
\]

where \(T\) is the useful symbol time and \(T_{s}\) is the total symbol time. Therefore it is a compromise between expected OBR reduction and efficiency. Simulations are performed for EGI lengths of 3%, 6% 12% and 24%, which corresponds to efficiencies of 91%, 89%, 84% and 76%.

For PSD results, it is convenient to define the normalized bandwidth \(B_n\)

\[
B_n = \frac{f}{N(\Delta f)} = fT
\]
A. Soft limiter (SL)

The AM/AM and AM/PM nonlinear characteristics of a soft limiter (SL) can be written as
\[
F[p] = \begin{cases} 
\rho & \rho \leq A, \\
A & \rho > A.
\end{cases}
\] (14)

Since the AM/PM component is zero the nonlinear characteristics of a SL can be written as
\[
g(x) = \begin{cases} 
x & |\rho| \leq A, \\
Ae^{\rho} & |\rho| > A.
\end{cases}
\] (15)

Although most physical components will not exhibit this piecewise linear behavior, the SL can be a good model if the nonlinear element is linearized by a suitable predistortor.

B. Solid-state power amplifiers (SSPA)

The input out relationship of many solid-state power amplifiers can be modelled as
\[
F[p] = \frac{\rho}{1 + (\frac{\rho}{2A})^{2p}}
\] (16)
\[
\Phi[\rho] = 0.
\]

where the parameter \(P\) controls the smoothness of the transition from the linear region to the limiting or saturation region. When, \(P \to \infty\) the SSPA model approximates the SL characteristics.

C. Travelling-wave tube (TWT)

The AM/AM and AM/PM characteristics for a TWT, according to [16] are,
\[
F[p] = \frac{\rho}{1 + (\frac{\rho}{2A})^{2}}
\] (17)
\[
\Phi[\rho] = \frac{\pi}{3} \rho^{3} + 4A^{2}.
\]

All these models give a maximum output signal of A. Input back off (IBO) used in these nonlinear devices can be defined in terms of A
\[
\text{IBO} = 10 \log_{10} \left( \frac{A^{2}}{E(x)^{2}} \right).
\] (18)

V. RESULTS

A 512 carrier OFDM system with quadrature phase shift keying (QPSK) and a GI of 32 is used in the simulations. The OFDM signal is passed through nonlinear devices described in Section 4. Both theoretical and simulated spectra of a conventional OFDM signal with 16, 64, 256 and 512 carriers are depicted in Fig. 2. Continuous lines represent the simulated results while discontinuous lines represent the theoretical results given by 9. No significant difference is observed between theoretical and simulated results. Both theoretical and simulated results show low OBR for larger N and the spectrum decreases more rapidly in the beginning, which is caused by the fact that the sidelobes are closer together. For 16, 64 256 and 512 subcarriers, the OBR at 4Bn are, -34dB, -40dB, -45dB and -50dB respectively. However, relatively large OBR is observed even for 512 subcarriers. The amount of OBR tends to increase further, if the OFDM signal passes through a nonlinear device. Next, the effect of EGI on the OBR of an OFDM signal in the presence of nonlinear devices is observed through simulations. Fig. 4 depicts the PSD for a SL with different IBOs. Curve 2 represents the OBR without an EGI. All other curves (1, 3, 4, 5) represent the PSD for with an EGI of 6%. Simulations results were obtained for IBO values of 5dB, 9dB and 11dB. OBR reductions at 2Bn are 43dB, 56dB, 68dB and 80dB respectively.

Next, the effect of EGI on the OBR of an OFDM signal is observed. For EGI of 3%, 6%, 12% and 24% the OBR reductions at 2Bn are, -34dB, -40dB, -45dB and -50dB respectively. However, relatively large OBR is observed even for 512 subcarriers. The amount of OBR tends to increase further, if the OFDM signal passes through a nonlinear device. Next, the effect of the length of EGI on the OBR when the signal is passing through SSPA and TWT respectively. Unlike in SL, a reduction in OBR is observed even for an IBO of 5dB. But these reductions are observed at 2.5Bn in the case of SSPA and after 1.75Bn in the case of TWT. Here again greater reductions are observed for larger IBOs. One important observation made at this point was the high OBR caused by TWT close to the signal band. As it can be seen in Fig. 6 high OBR exists within Bn and 2Bn. This OBR can not be reduced significantly by using EGI. However, high OBR reduction is observed in the region beyond 2Bn in the case of TWT compared to other two non-linearities. Next we study the effect of the length of EGI on the OBR when the signal is passing through a nonlinear device.
Fig. 4. Power spectral density of an OFDM signal passing through a SL with different IBOs (EGI=0,16).

Fig. 5. Power spectral density of an OFDM signal passing through a SSPA with different IBOs (EGI=0,16).

Fig. 6. Power spectral density of an OFDM signal passing through a TWT with different IBOs (EGI=0,16).

Fig. 7. Power spectral density of an OFDM signal with different EGIS passing through a SL (IBO=9dB).

Fig. 8. Power spectral density of an OFDM signal with different EGIS passing through a SSPA (IBO=9dB).

Fig. 9. Power spectral density of an OFDM signal with different EGIS passing through a TWT (IBO=9dB).

Fig. 10. Power spectral density of an OFDM signal with different EGIS passing through different nonlinear devices. The EGI is fixed to 6% for this simulation result. When the IBO is just 5dB, the OBR levels from all three nonlinearities are same until the normalized frequency of 2. Beyond this point TWT non-linearity has less OBR compared to SSPA and SL. This difference is about 50dB at normalized frequency of 4. When SSPA and SL is compared, it is observed that both has almost similar performances close to the useful frequency band, while TWT has about 10dB less radiation at 4B0. When the IBO is increased to 9dB, the OBR caused by SSPA and SL decrease by about 20dB at 2B0. There is only about 5dB reduction in OBR due to TWT in this region. Results indicate that the use of EGI effect differently on different non-linearities. It also suggests that we have to maintain a sufficient IBO in order to reduce OBR caused by non-linearities. Fig. 11 shows the reduction in OBR with different windowing functions. Four types of windowing functions, Hamming, Hanning, raised cosine and Blackman are simulated. Here, the Blackman window is defined as
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