Project	**IEEE 802.16 Broadband Wireless Access Working Group <http://ieee802.org/16>**
Title	**Performance aspects of OFDM PHY proposal**
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Abstract	Several PHY aspects of OFDM proposal are studied
Purpose	
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PHY performance aspects of OFDM proposal

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1. Introduction

In this contribution, the several PHY aspects of the OFDM proposal are studied. In particular the following aspects are studied:

- Performance in multipath conditions.
- Phase noise immunity.
- Required Power Amplifier Backoff for regulatory conformance.

2. Performance in Multipath

In this section the immunity to multipath is analyzed. This is achieved by observing the Packet Error Rate (PER) as a function of the received Signal to Noise Ratio (SNR) for various multipath conditions.

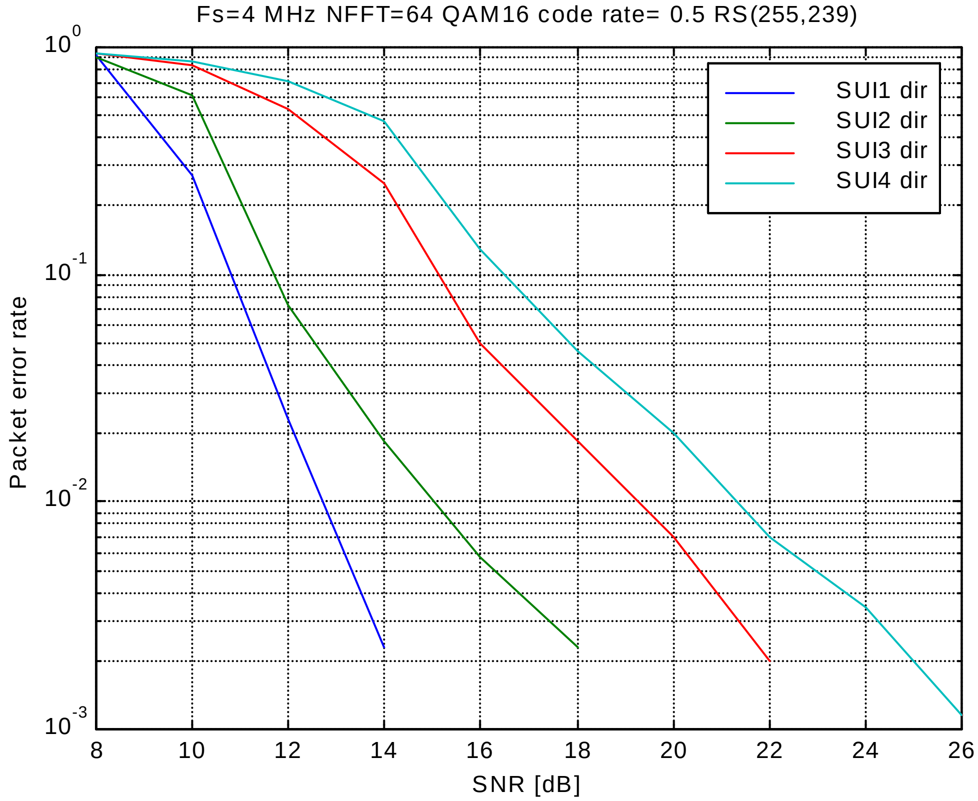
2.1. Simulation conditions

- The system was simulated by generating OFDM packets, passing them through the channel model and receiving them with an OFDM receiver. In all simulations 1000 bytes packets were used.
- The channel model was simulated according to the models given in [2]. The Matlab M-File that was used for generating the channel response is given in Appendix A.
- The resulting impulse responses were normalized to unity gain per ensemble. That is, the <u>ensemble</u> average of the tap weights power was normalized to unity.
- For each generated packet, and for each evaluated channel model, a different channel impulse response was selected at random. The same impulse response was then evaluated for various SNRs. The ensemble averaged PER was then shown as a function of SNR.
- The OFDM system employed rate ½ K=7 convulotional codes, and a (255,239,8) Reed –Solomon code. In all cases a random bit-interleaver was used.
- The FFT length studied was in the range of 64-1024 points. The complex sampling rate was assumed to be 4Ms/sec. The guard interval was set 1/8 of the FFT period except for the case of 64 points FFT for which 16 point guard interval was used.
- Perfect Channel State information was assumed, and the effects of estimation and training were not simulated. Likewise, the effects of phase and power amplifier non-linearity were not simulated.

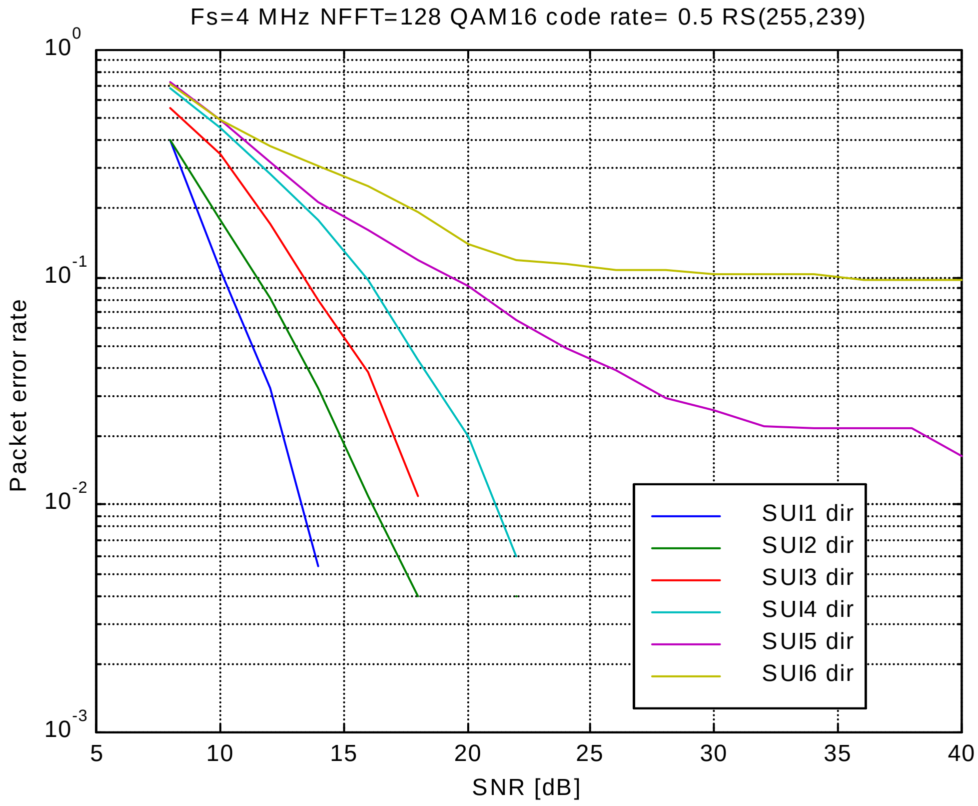
2.2. Simulation Results – Convolutional and RS(255,239) code

2.2 1. FFT=64 points

For the 64 point FFT, the performance are limited by Inter-Symbol Interference (ISI). This limits the operation to SUI4 model.

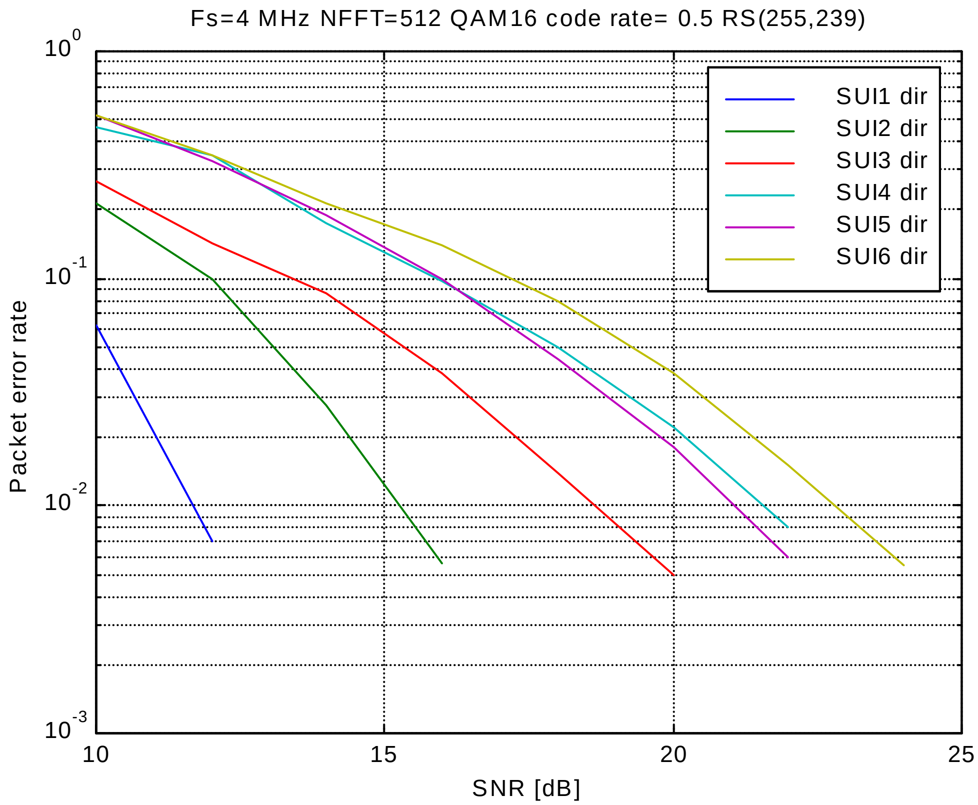


2.2 2. FFT=128 points



2.2 3. FFT=512 points

With an FFT size of 512 the performance is no longer limited by ISI. The system can cope with high index SUI models.



3. Phase-Noise Immunity

The phase-noise problem is omnipresent in all high-efficiency microwave communication systems. This section analyzes the effects of phase noise on OFDM performance. The analysis follows the excellent tutorial of Stout [3]. First we summarize the results of [3]. Then we proceed by introducing a simplified model for phase noise. Lastly the phase noise spectrum of a specific microwave oscillator is used to evaluate the phase-noise induced distortion.

3.1. Some results on phase noise and OFDM

This section summarized the results given in [3].
Consider an OFDM system degraded by an oscillator phase noise. Let us denote by

T - the OFDM symbol duration
$f_u=1/T$ –the intercarrier spacing
$P_\varphi(\omega)$- the power spectral density of the phase noise process in rad^2/Hz

The phase noise effect can be broken into two phenomena:

1. Common Phase Error (CPE)
2. Intercarrier Carrier Interference (ICI).

The effect of CPE is that all subcarriers are rotated by a common random angle. The Noise/Signal ratio resulting from CPE effect is given by:

$$\left(\frac{N}{S}\right)_{CPE} = \int_{-\infty}^{\infty} \sin c^2(f)W(f)df \qquad (1)$$

The CPE can be corrected, almost completely, by using pilot subcarriers. Hence it will not considered here.

The ICI effects are due to the loss of orthogonality incurred by the phase noise process. The noise /signal ratio caused by ICI is given by:

$$\left(\frac{N}{S}\right)_{ICI} = \int_{-\infty}^{\infty} P_{\varphi}(f)W(f)df \qquad (2)$$

Where the *W(f)* is given by

$$W(f) = \sum_{n\neq 0} \mathrm{sinc}^2\left(\frac{f}{f_u} + n\right) \qquad (3)$$

3.2. A specific Oscillator example

To evaluate (2) we shall use a simple one pole model for the phase noise process. While being somewhat simplified, this model still captures the important effects of phase noise related degradation.
The phase noise PSD is therefore given by:

$$P\varphi(f) = \frac{\Phi_0^2}{\pi f_c} \frac{1}{1+(f/f_c)^2} \qquad (4)$$

where Φ_0^2 is the integrated RMS power of the phase noise process and f_c is the 3dB corner. Combining (2) (3) (4) we get:

$$\left(\frac{N}{S}\right)_{ICI} = \frac{2\Phi_0^2}{\pi} \frac{f_u}{f_c} \int_0^{\infty} \frac{1}{1+\left(\frac{f_u}{f_c}\cdot f\right)^2} \sum_{n\geq 1} \mathrm{sinc}^2(f-n)df \quad (5)$$

For a specific oscillator operating at 5.7GHz, we got the following parameters:

Φ_0^2 = -35dBc

f_c= 10KHz

The single-sided PSD of this particular phase noise process is shown in Figure 1.

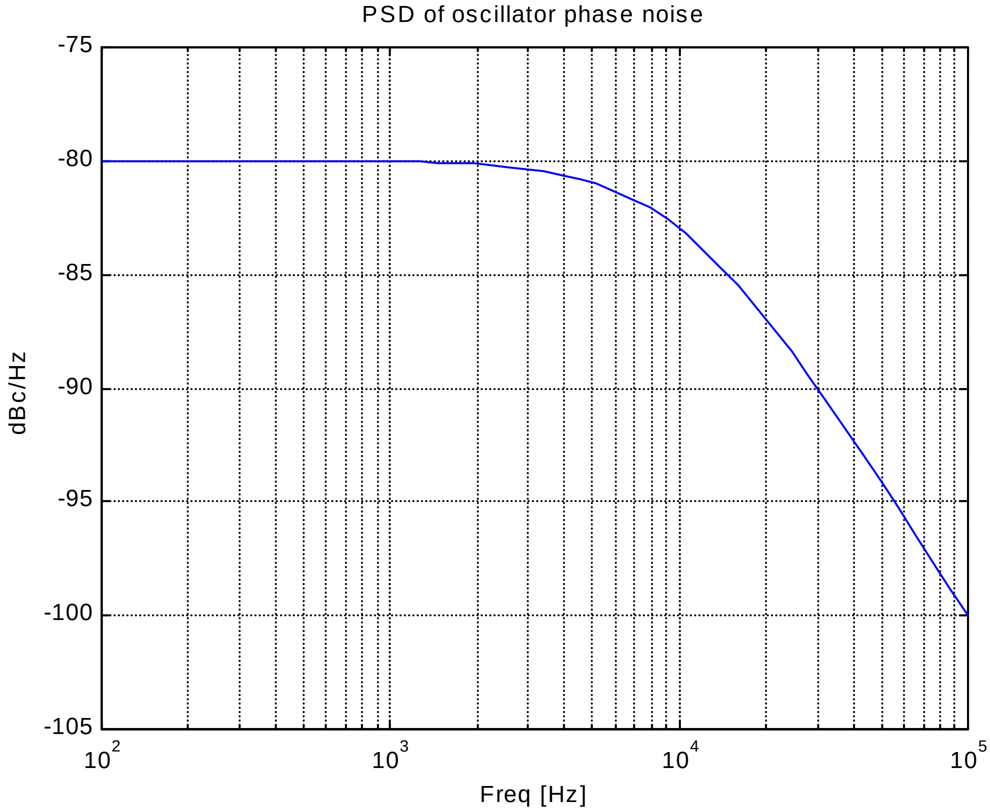


Figure 1 PSD of phase noise process

These values, were used to produce Figure 2, where the resulting ICI induced SNR is plotted as a function of the carrier spacing f_u.

We should note that above analysis assumed that there is only one non-ideal oscillator in the system. However, all communication systems employ a transmitting side and a receiving side. Thus, if both sides employ the same oscillator, the results will be worse by 3-dBs.

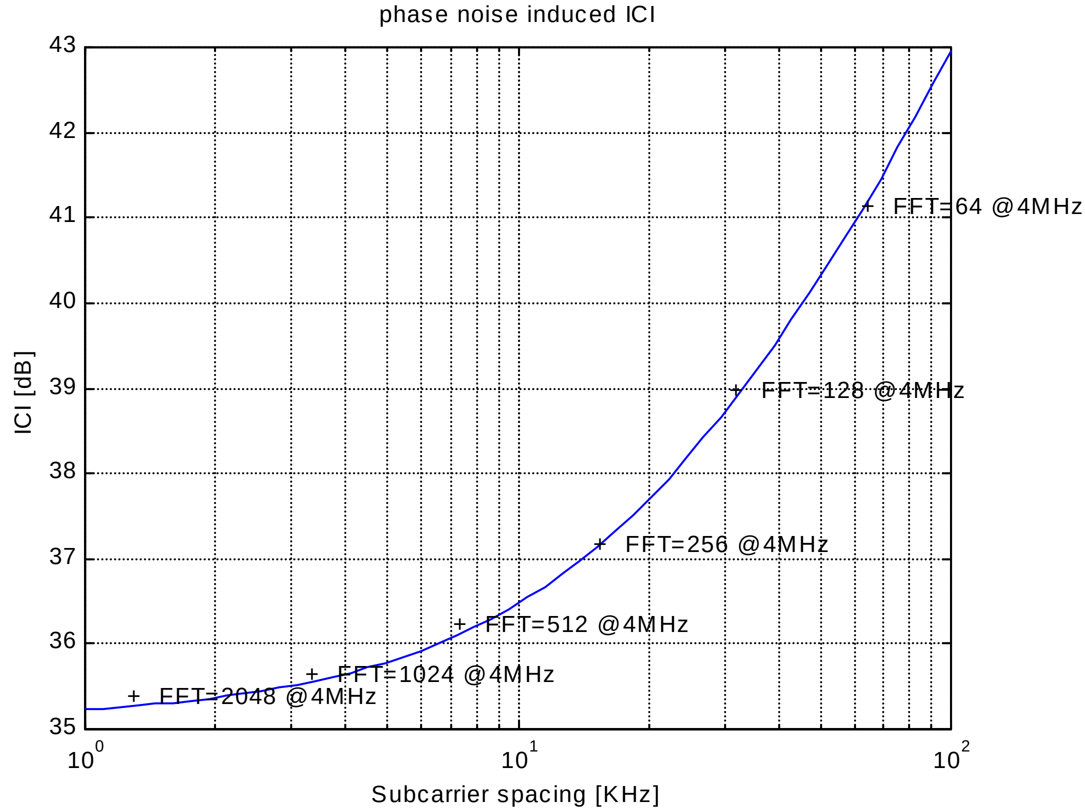


Figure 2 ICI induced SNR vs. Subcarrier spacing

3.3. Conclusions

The ICI induced SNR is lower bounded by the integrated phase noise of the oscillator. For typical oscillators this value is about –35dBc. This may be sufficient QAM64 operation. With high subcarrier spacing the resulting SNR is even higher.

4. Required Power Amplifier Backoff

Here we study the Power Amplifier backoff required to conform to regulatory spectral masks. A comparison to single carrier modulation with QAM16 is also provided.

4.1. HPA model

Here we shall use the well-known Rapp model [4]. Consider a complex baseband notation. Let us denote by v_{IN} and v_{OUT} the input and output complex signals, respectively. Let $P_{SAT} = |v_{SAT}|^2$ denote let the saturated power of the amplifier be $P_{SAT} = |v_{SAT}|^2$. Then the relation between v_{IN} and v_{OUT} is given by:

$$v_{OUT} = v_{IN} \Big/ \left(1 + \left(|v_{IN}| / v_{SAT}\right)^{2P}\right)^{1/(2P)},$$

where P is called the knee parameter.

For HPAs in the sub5GHz band, measurements revealed that typical values of P are in the range of 2-4. Here we shall assume P=2.

4.2. Conformance to ETSI masks

The PSD density of an OFDM signal and the relevant ETSI mask (types E, F and G) are also shown in Figure 3. The OFDM signal is distorted by a PA with input backoff levels of –12…-6dB. It can be observed that 8dB backoff is required.

The OFDM parameters are as follows:

- 512 FFT with raised-cosine window.
- 4Ms/sec complex sampling rate
- 75% active subcarriers.

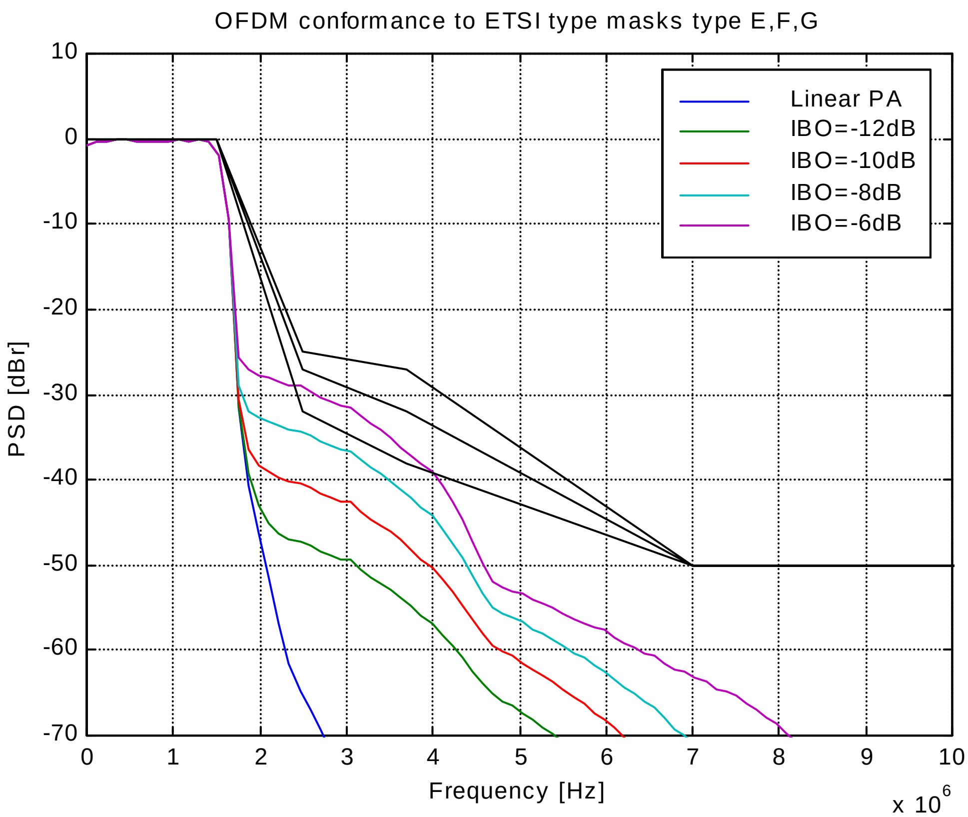


Figure 3 OFDM conformance to ETSI mask

4.2 1. Comparison with single-carrier modulation

For comparison, the PSD on the distorted single carrier signal is plotted in Figure 4. The parameters of the single carrier signal are:

- QAM16 modulation

- Square root raised-cosine pulses with rolloff=0.1
- 2.8Ms/sec symbol rate. This is called to occupy roughly the same B/W as the OFDM signal.

In this a 6dB backoff is required.

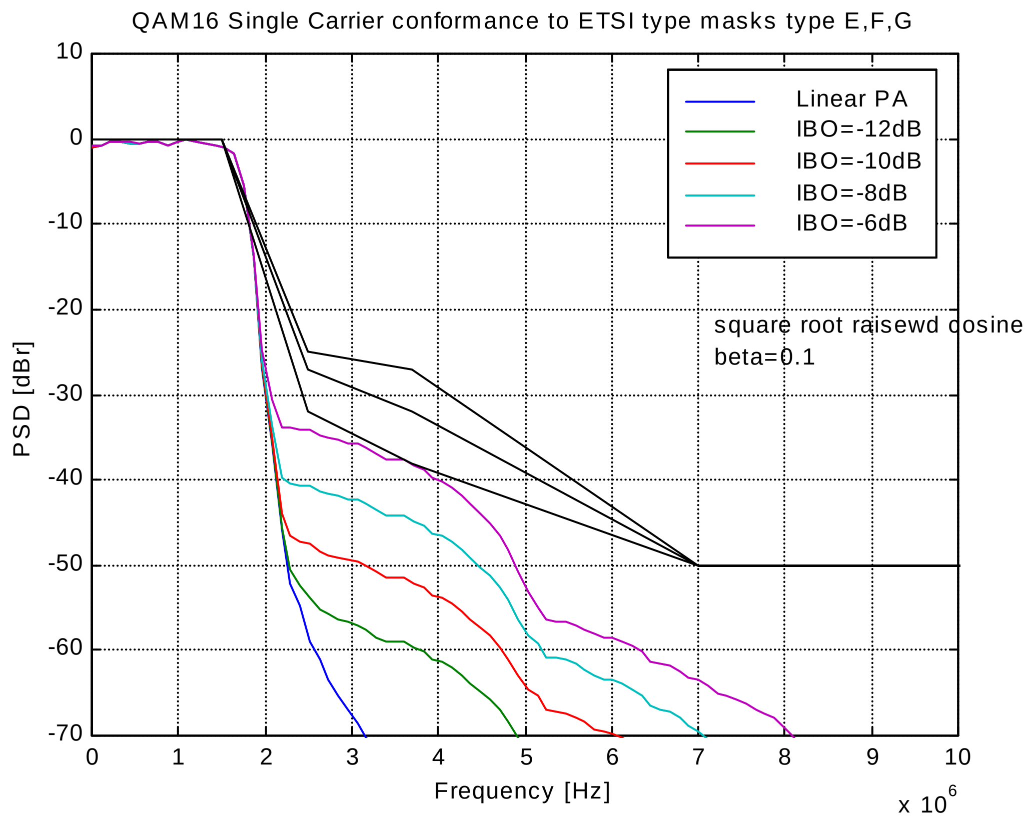


Figure 4 Single Carrier conformance to ETSI masks

4.3. Conformance to MMDS masks

Here we consider 1/3 MMDS channel operation. The OFDM signal is shown in Figure 5. The single carrier is shown in Figure 6. For the OFDM case a backoff of 10dB is required. For the MMDS 8dB backoff is required.

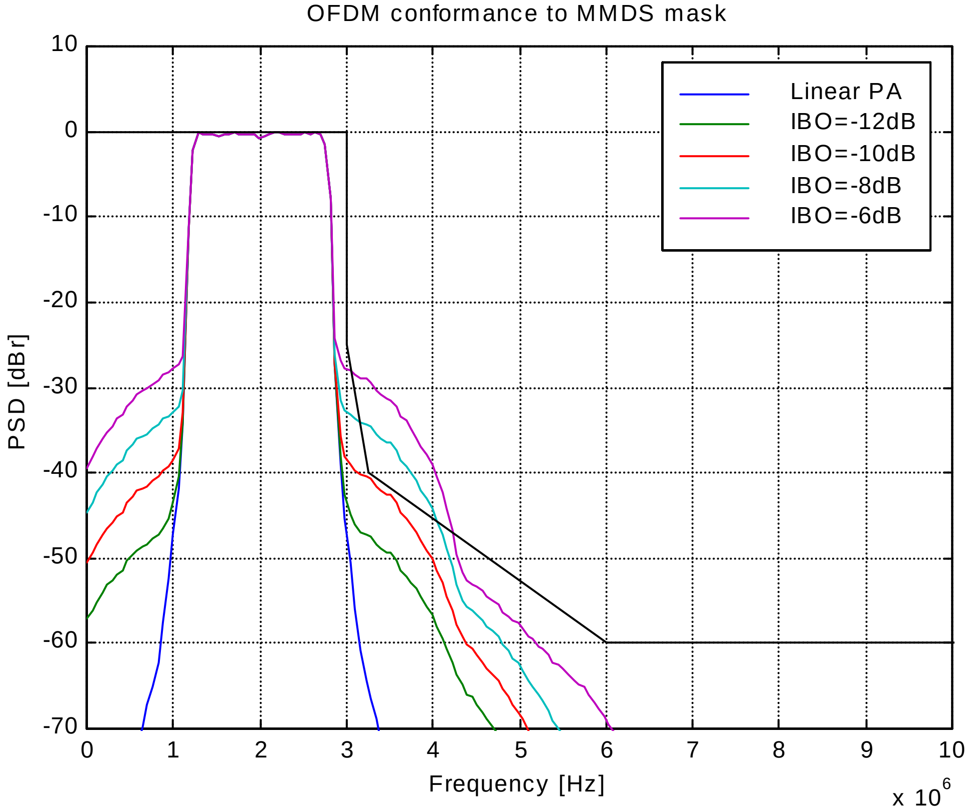


Figure 5 OFDM Compliance

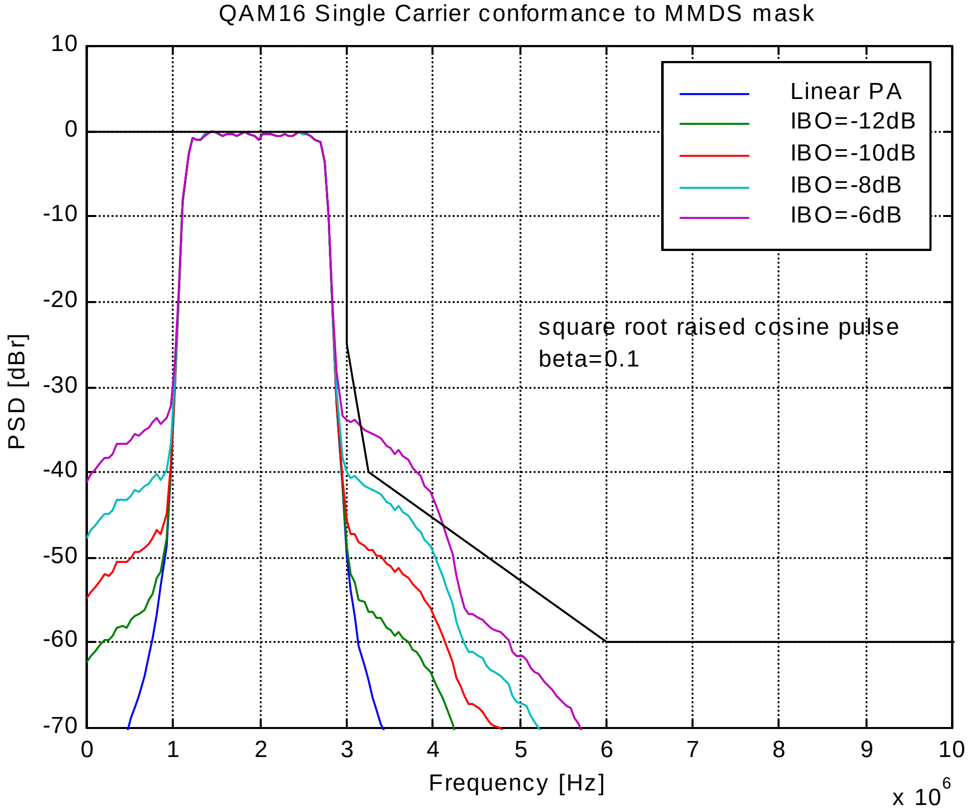


Figure 6 SC MMDS compliance

4.4. Conclusions

The PA backoff, required to meet regulatory requirements, is about 8-10dB for the OFDM case, and 6-8 dB for the QAM16 single-carrier case.

5. References

[1] "OFDM proposal for IEEE 802.16a PHY draft standard", IEEE 802.16.3c-01/33r2

[2] V. Erceg et. Al. "Channels models for Fixed Wireless Applications" IEEE 802.16.3c-01/29r1

[3] J. Stout 'The effects of Phase noise in COFDM' EBU technical review Summer 1998. http://www.bbc.co.uk/rd/pubs/papers/pdffiles/jsebu276.pdf

[4] Rapp, C. "Effects of HPA non-linearity on 4-DPSK/OFDM Signal for Digital Sound Broadcasting System" *Proceedings of the Second European Conference on Satellite Communications*, Liege Belgium pp.179-184, Oct 22-24 1991.

Appendix A

```
%generate channel model per Stanford University Interim (SUI) model
%per IEEE802.16.3c-01/29r1
%
%use:
%[imp taps] = function SUI_model(SUI_indx, direct, fs );
% where:
%SUI_indx: index of SUI model allowed range 1...6
%direct:   usage of directional antenna at CPE. 0=> omni 1=>directional
%fs:       sampling rate in MHz
%imp:       generated impulse response
%taps:      non-zero taps of impulse response
%Tal Kaitz 6/3/01


function [imp, taps] =SUI_model(SUI_indx, direct, fs );

% check for input parameter range
if ~ismember(direct,[0,1])
   error('direct must be in the range [0,1]' );
end;
if ~ismember(SUI_indx,[1:6])
   error('direct must be in the range 1:6' );
end;

%model information matrix
SUI1_omni=[...                %SU1 omni model
      0  0.4   0.8; ...       %tap delay in uSe
      0  -15   -20;...        %relative power
      4  0     0 ];           %K factor per tap

SUI1_dir=[...                 %SU1 deirectional 30deg model
      0  0.4   0.8; ...
```

```
      0  -21   -32;...
      16  0     0 ];

SUI2_omni=[...                %SU2 omni model
      0  0.5   1.0; ...
      0  -12   -15;...
      2  0     0 ];

SUI2_dir=[...                 %SU2 omni model
      0  0.5   1.0; ...
      0  -18   -27;...
      8  0     0 ];


SUI3_omni=[...                %SU3 omni model
      0  0.5   1.0; ...
      0  -5   -10;...
      1  0     0 ];

SUI3_dir=[...                 %SU3 dir model
      0  0.5   1.0; ...
      0  -11   -22;...
      3  0     0 ];

SUI4_omni=[...                %SU4 omni model
      0  2     4; ...
      0  -4   -8;...
      0  0     0 ];

SUI4_dir=[...                 %SU4 dir model
      0  2     4; ...
      0  -10   -20;...
      0  0     0 ];

SUI5_omni=[...                %SU5 omni model
      0  5  10; ...
      0  -5   -10;...
      0  0     0 ];

SUI5_dir=[...                 %SU5 dir model
      0  5  10; ...
      0  -11 -22;...
      0  0     0 ];

SUI6_omni=[...                %SU6 omni model
      0  14    20; ...
      0  -10   -20;...
      0  0     0 ];


SUI6_dir=[...                 %SU6 dir model
      0  14    20; ...
      0  -16   -26;...
      0  0     0 ];


%overall SUI model
SUI={SUI1_omni SUI2_omni   SUI3_omni   SUI4_omni   SUI5_omni   SUI6_omni ;
     SUI1_dir  SUI2_dir    SUI3_dir    SUI4_dir    SUI5_dir    SUI6_dir};


%select a specific model
SUI_mod=SUI{direct+1,SUI_indx};
```

```
%number of taps
n=size(SUI_mod,2);
%location of taps
locs=1+round(SUI_mod(1,:)*fs);
imp=zeros(1,max(locs));

%get taps
taps=gen_rice(10.^(SUI_mod(2,:)/10)... %power of taps
               ,SUI_mod(3,:),...       %K factor of taps
               1);                     %normalize the result
imp(locs)=taps;
```

```
%generate a ricean distributed flag
%s:  power in two dimensions
%k:  factor linear
%normalize:  0 don't normalize 1=>normalize such that E{x*x'}=1;
%x resulting ricean vector.
%
%s can be a vector. in this case the x contains length(s) i.i.d RV
%if length(s)==length(k) then k is taken  element per element
%length(k)==1 then k applies only to the first element

function x=gen_rice(s,k,normalize)

%make row vectors and complete k to s by adding zeros
s=s(:)';
k=[k(:)' zeros(1,length(s)-length(k))];

n=length(s);

%variance (per one dimension) of scatter part
sigm2=s./(k+1)/2;
%power of  ricean part
a2=s.*k./(k+1);

%generate vector

x=sqrt(a2).*exp(j*2*pi*rand(1,n))+ sqrt(sigm2).*([1 j]*randn(2,n));

%normalize if necessary
if (normalize),
   %profile
   prof=[a2+2*sigm2];
   norm_fac= sqrt(prof*prof');
   x=x/norm_fac;
end
```