

PERFORMANCE REQUIREMENTS OF BANDPASS SIGMA-DELTA CONVERTERS IN OFDM SYSTEMS

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Abstract: *This paper analyzes the effect of analog-to-digital bandpass Sigma-Delta conversion on the performance of Orthogonal Frequency Division Multiplexing (OFDM) systems. A brief description of both OFDM systems and the related simulation model is given. The nonlinear effects of quantization overload on overall OFDM performance are evaluated in terms of quantization noise power and bit error rate. It is shown how minimizing quantization noise power can lead to suboptimal results. Moreover a set of minimum performance requirements for Sigma-Delta converters is established.*

Keywords: OFDM, Sigma-Delta, overload effects

1. INTRODUCTION

An essential feature of Digital Communication Systems (DCS) is the Analog to Digital (A/D) and Digital to Analog (D/A) data conversion. A/D and D/A converters have been initially used to digitize analog signals and transmit them via a DCS, so taking advantage of the more robust performance of these systems with respect to analog ones. When used in this way, the data conversion does not operate on the modulated waveforms used to actually transmit the messages, so its influence regards mainly the quality of the message to be transmitted, not the quality of the RF transmission. Thus, the related effects on the overall DCS performance can usually be neglected.

A more recent usage of such converters is made by Direct Digital Modulation (DDM), according to which the transmitter D/A converts a digital version of baseband modulated waveforms, obtained throughout digital processing. The receiver usually shows a specular structure. In fact, the received signal is quantized by an A/D converter and then a digital demodulation is performed. When used in this way D/A and A/D converters operate directly on the modulated signal, so that their characteristics possibly influence the overall performance of the DCSs in which they are embedded [1].

By following the common tendency to replace analog signal processing with digital signal processing, the newest DDM systems often perform a digital IF bandpass conversion of modulated signals. Thus higher performance and more reproducible results are obtained at the expense of more severe converter requirements [2][3]. Consequently, analyzing the impact of converter unidealities upon the overall system behavior is an important step in a DCS design and optimization process.

In the following, A/D bandpass IF conversion will be considered when applied to Orthogonal Frequency Division Multiplexing (OFDM) DCS receivers. OFDM is a very robust DCS technique, adopted for the Digital Audio Broadcasting (DAB), the Digital Video Terrestrial Broadcasting (DVB-T) and proposed for local area wireless networks such as the HIPERLAN [4]-[6]. Under the name of Discrete Multitone (DMT) it is also used in Asymmetric Digital Subscriber Lines (ADSL) systems [7].

A particular attention will be given to Sigma-Delta converters. Due to their superior performance and quantization noise shaping features these converters are the subject of several research activities. Moreover, such converters can be easily integrated in CMOS technology, so that they are good candidates for mobile receivers [8][9].

The behavior of Sigma-Delta converters fed with Gaussian distributed signals and the performance of Sigma-Delta bandpass conversion in OFDM receivers have been already analyzed and discussed in the literature [10][11]. However the effects of nonlinear phenomena introduced by Sigma-Delta conversion on the efficiency of an OFDM system have not been deeply investigated yet. The main purpose of this work is to show how Sigma-Delta quantizer overload can not be underestimated, and how minimizing the quantization noise power of an A/D converter embedded in an OFDM system does not necessarily lead to the optimal overall performance. The obtained results will then be used to establish a minimum set performance requirements to Sigma-Delta ADCs.

2. BASIC OF OFDM SYSTEMS

The main idea behind OFDM is to split the input digital data stream to modulate a large number of carriers. The multiple carriers can then transmit data at a very low symbol rate. Usually, a set of carriers equally spaced in frequency is modulated by a sequence c_k of complex Quadrature Amplitude Modulation (QAM) symbols by means of an Inverse Fast Fourier Transform (IFFT):

$$s[n] = \frac{1}{N} \sum_{k=0}^{N-1} c_k e^{j \frac{2\pi nk}{N}}, \quad n = 0 \dots N-1 \quad (1)$$

Then the sequence s feeds a D/A converter to produce an analog signal.

The receiver has a specular structure and operates an A/D conversion followed by a Fast Fourier Transform (FFT),

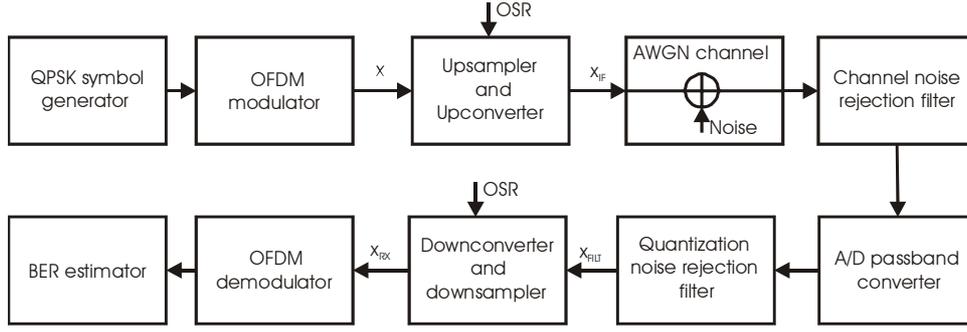


Fig. 1: simulation block scheme

which demodulates the received carriers. The low symbol rate, together with the insertion of a guard time, effectively allows the suppression of multipath phenomena. Coupled with channel coding, OFDM is one of the most robust and band efficient techniques currently available. One of the peculiar characteristics of OFDM signals is the high peak-to-mean power ratio, which requires systems with high dynamic range.

In this paper a DVB-T 2k like OFDM system will be considered, counting 2048 carriers, of which only the inner 1705 ones, that is the closest to the central frequency, are active [5]. Each carrier uses a QPSK modulation scheme, and each OFDM symbol conveys 1705 QPSK symbols. DVB-T is a good example of an OFDM system, and the results obtained for such a case hold also for other OFDM DCSs.

The system performances will be mostly evaluated in terms of channel bit error rate (BER). DVB-T specific features like channel coding, interleaving, guard time insertion and pilot tone insertion will not be considered because they do not affect the performance analyzed in this work [5].

3. THE SIMULATED OFDM SYSTEM

Fig. 1 shows the block scheme of the simulated OFDM system. The first three blocks model an OFDM transmitter, the fourth block implements an Additive White Gaussian Noise (AWGN) channel and the remaining blocks represent an OFDM receiver. The symbol generator produces vectors d of $N_{OFDM}=1705$ independent identically distributed QPSK symbols. The OFDM modulator processes the input QPSK coefficients by performing an IFFT of size $N=2048$ [5]:

$$x[n] = \frac{1}{N} \sum_{k=0}^{N_{OFDM}} d_k e^{j \frac{2\pi n}{N} \left(k - \frac{N_{OFDM}-1}{2} \right)}, \quad n = 0 \dots N-1 \quad (2)$$

The frequency shift in (2) is introduced in order to achieve the carrier allocation specified in the DVB-T standard [5].

The following block in Fig.1 upsamples the signal using an assigned Over Sampling Ratio (OSR) and then performs a $\pi/2$ frequency shift as follows:

$$x_{IF}[n] = \text{Re} \left\{ x_{UP}[n] \cdot e^{j \frac{n\pi}{2}} \right\}, \quad n = 0 \dots N \cdot OSR - 1 \quad (3)$$

where $\text{Re}\{\}$ is the real part operator and x_{UP} is the upsampled version of the modulator output x .

Notice that the corresponding analog Intermediate Frequency (IF) is one quarter of the sampling frequency of the upsampled signal. It has been shown to be the optimal choice for a Sigma-Delta bandpass converter with respect to spectral symmetry and phase linearity of the noise transfer function [11]. Moreover, as the IFFT generates a baseband signal sampled at its Nyquist rate, digital upconversion requires intrinsically an OSR of at least two.

According to the Central Limit Theorem, both the baseband and the IF upconverted signal have a Gaussian statistic. This has been verified throughout meaningful simulations, whose results have been reported in the histogram plotted in Fig.2.

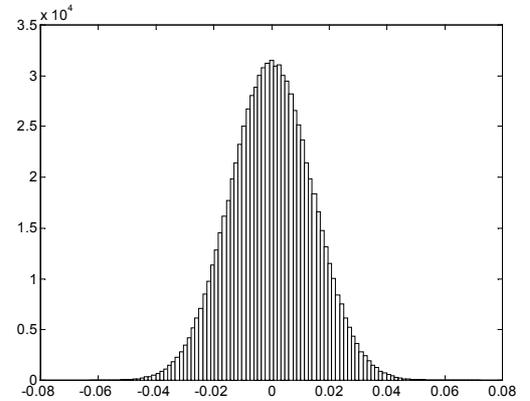


Fig. 2: OFDM-IF distribution, obtained from a record of 100 OFDM-IF symbols

The AWGN block simulates the transmission channel by adding noise in such a way that the output of the bandpass filter exhibits the desired Signal to Noise Ratio (SNR). The following noise rejection filter has a bandpass rectangular frequency response centered at $\pi/2$, and a bandwidth equal to $2\pi/OSR$.

Both a PCM or a Sigma-Delta conversion can be performed by the A/D converter block. The following filter removes the out-of-band quantization noise, so it has the same characteristics of the previously described channel noise rejection filter. Combined with the downconverter and

downsampler block, this architecture works indifferently with the uniform quantization law or with a bandpass Sigma-Delta modulator.

If x_{FILT} represents the output of the quantization noise rejection filter, the downconverted signal x_{BB} can be expressed as follows:

$$x_{BB}[n] = 2x_{FILT}[n] \cdot e^{j\frac{n\pi}{2}}, \quad n = 0 \dots N \cdot OSR - 1 \quad (4)$$

A complex valued sinewave is used in (4) rather than a real-valued one in order to recover both the In-phase (I) and Quadrature (Q) components of the transmitted baseband OFDM signal. The downsampler operates in a specular way with respect to the transmitter upsampler. After a rectangular lowpass filtering with π/OSR cutoff frequency, it reduces the sampling rate by a factor OSR.

The downsampler output x_{RX} feeds an OFDM demodulator, which performs an FFT to recover an estimate d' of the transmitted QPSK symbols:

$$d'[k] = \sum_{n=0}^{N-1} x_{RX}[n] \cdot e^{-j\frac{2\pi nk}{N}}, \quad k = 0 \dots N_{OFDM} - 1 \quad (5)$$

Finally, the last block in Fig.1 compares the received QPSK symbols with the transmitted ones, and calculates the BER.

4. SIMULATION RESULTS

The Sigma-Delta converter considered in this paper is obtained by inserting into a first order architecture the following bandpass loop filter:

$$H_{bp}(z) = \frac{-z^{-2}}{1+z^{-2}} \quad (6)$$

Simulations were carried on by feeding the Sigma-Delta modulator with several consecutive OFDM-IF symbols for different quantizer resolutions. The quantization step Δ was varied in order to determine the minimum value of the quantization error standard deviation σ_q referred to the input signal standard deviation σ_i . At first, the Sigma-Delta converter was analyzed as a standalone component. The results achieved for OSR=4,8,12 are reported in Fig. 3. Notice that all curves have a minimum. In fact, larger values of Δ increase the granular noise. Conversely, when Δ is small quantization noise increases due to overloading effects.

The optimum quantizer step/input signal standard deviation ratio was found to be between 1.5 and 2.6 and grows with OSR. As no hypothesis were made about the OFDM-IF signal, Fig.3 holds also for a generic zero mean Gaussian input.

For comparison, the influence of overload on quantization noise has been analyzed also in PCM converters. Simulation results are reported in Fig. 4 for ADC with 2,3,4 and 8 bits. They show that optimal Full Scale/ σ_i ratio is between 1.6 and 3.7. Notice that the optimal ADC dynamic range increases with the number of bits.

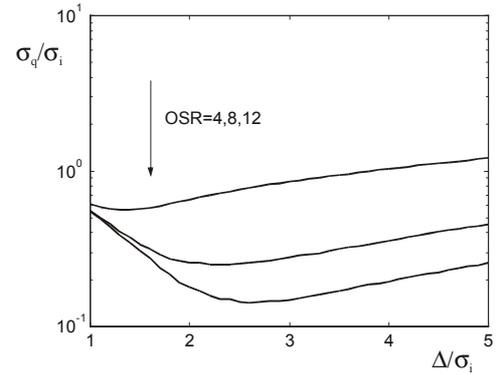


Fig. 3: Normalized quantization error standard deviation vs quantizer resolution; 1 bit Sigma-Delta converter

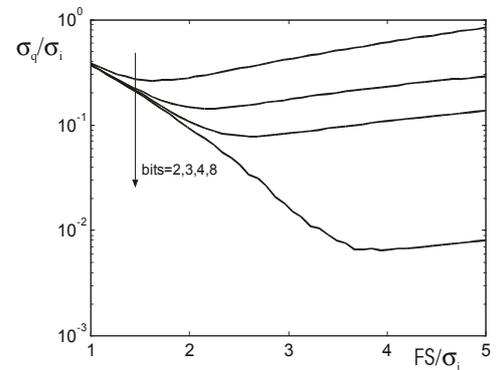


Fig. 4: Normalized quantization error standard deviation vs quantizer full scale (FS); PCM converter

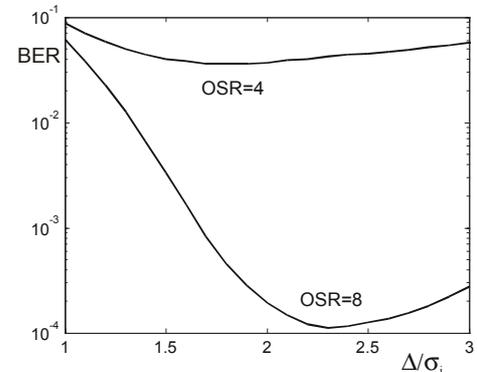


Fig. 5: Bit Error Rate vs quantizer resolution, 1 bit Sigma-Delta converter

Further simulations, in which the Sigma-Delta converter was embedded into an OFDM DCS operating on a noiseless channel, showed however that the best overall performances (expressed in terms of BER) are achieved for Δ/σ_i higher than the ones related to the quantization noise power, as shown in fig. 5. Similar results, with a smaller difference between the BER and σ_q optimal values, have been obtained also for PCM quantizers. Such a behavior is probably due to the statistical properties of quantization noise when overload occurs.

The impact of Sigma-Delta converter performance on an OFDM system has been also analyzed in presence of channel

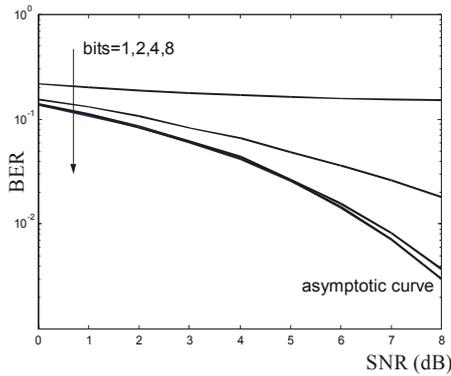


Fig. 6: BER vs. SNR: PCM converter and optimal value of Δ

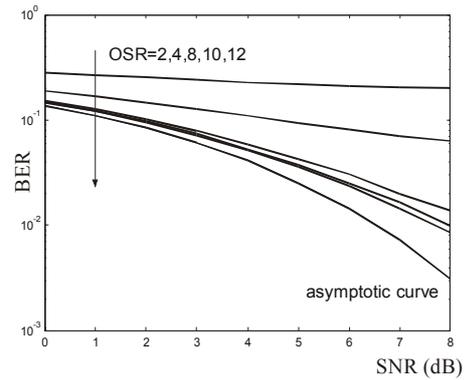


Fig. 7: BER vs. SNR: 1 bit Sigma-Delta converter Quantization and optimal value of Δ

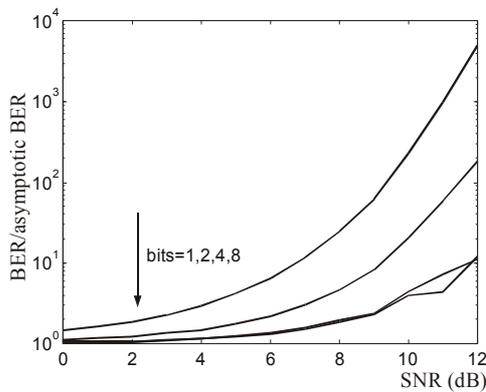


Fig. 8: BER variation vs. SNR: PCM converter

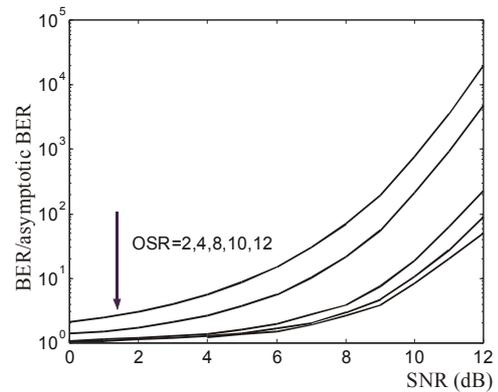


Fig. 9: BER variation vs. SNR: 1 bit Sigma-Delta converter

AWGN. Since the OFDM-IF signal and the channel noise are both normally distributed and independent, also the noisy signal has a Gaussian distribution. Consequently, the quantization noise power minima occur at the same Δ/σ_i values of Fig. 3 and 4, but now σ_i is the sum of both signal and channel noise powers.

Moreover, simulations show that adding channel noise does not change the Δ/σ_i ratio corresponding to the BER minima.

Various BER vs. SNR curves, obtained throughout Montecarlo simulations are reported in Fig. 6 and Fig. 7, for PCM and Sigma-Delta converters respectively. In both figures Δ/σ_i ratios corresponding to the BER optimization are considered. Moreover an asymptotic curve, corresponding to the behavior of an infinite resolution quantizer, is depicted. The considered SNR range includes the threshold value for DVB-T 2k systems, which is around 6-7dB for QPSK transmissions [5]. To analyze the performance degradation introduced by the A/D conversion, the ratio between the achieved BER and the asymptotic BER is reported in Fig. 8 and Fig. 9 for PCM and Sigma-Delta converters respectively.

It can be observed that while a PCM converter needs at least 4 bits of resolution to achieve a negligible noise margin loss, a Sigma-Delta converter requires an OSR greater than 12. As OFDM DCSs can require large signal bandwidths (8 MHz for a DVB signal) this could lead to excessively high

sampling rates, at least for a CMOS technology. However, the adoption of higher order and multibit Sigma-Delta structures would probably relax such requirements.

5. CONCLUSIONS

The effect of Sigma-Delta bandpass conversion on the overall performance of an OFDM DCS has been analyzed and compared with the one characterizing PCM conversions. Simulations confirm that ADC overload gives a significant contribution to BER performance degradation and cannot be neglected. In particular it was shown that optimal BER performance is achieved throughout a tradeoff between overload and granular noise, rather than a simple quantization noise power minimization.

Expected future developments are a compared analysis of the performance achieved by using multibit and higher order Sigma-Delta converters.

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