OFDM PERFORMANCE IN AMPLIFIER NONLINEARITY

S. MERCHÁN[1], A. GARCÍA ARMADA[2] AND J. L. GARCÍA[1]

[1] *University of Cantabria. Department of Communications Engineering. E.T.S.I.I. Telecomunicación. Spain.*

[2] *Polytechnical University of Madrid. Department of Signals, Systems and Radiocommunications. E.T.S.I. Telecomunicación. Spain.*

ABSTRACT

The activities of the current European RACE and ACTS projects have led to an increasing interest in OFDM (Orthogonal Frequency Division Multiplexing) as a means of combating impulsive noise and multipath effects and making fuller use of the available bandwidth of the system. This paper analyses the performance of OFDM signals in amplifier nonlinearity. In particular, bit error rate (BER) degradation as a result of amplitude limiting or clipping are analysed. In the presence of both nonlinear distortion and additive Gaussian noise, optimized output power back off is provided to balance the requirements of minimum BER and power amplifier efficiency. For this purpose, an OFDM system has been built using the SPW [1] (Signal Processing Worksystem) simulator.

1. INTRODUCTION.

Considerable research has been done in Europe on OFDM and a great deal of progress has been made in developing it for digital television broadcasting. OFDM has already been implemented in digital audio broadcasting and is being tested for Digital Television Terrestrial Broadcasting (dTTb) [2]. It is also being studied for broadband cellular distribution systems of digital TV and interactive services, where Microwave Video Distribution Systems (MVDS) are used.

To apply OFDM to these systems, is usually required an increase in the power of the transmitted signal. However, the high peak-to-average power ratio of an OFDM signal makes it susceptible to nonlinear or clipping distortions as the signal peaks may occasionally thrust into the saturation region of the power amplifier. This paper studies the effects of nonlinear behaviour of the power amplifier (i.e. amplitude distortion) on the performance of the OFDM system.

2. OFDM CONCEPT.

Orthogonal Frequency Division Multiplexing is one of the best alternatives for alleviating multipath effects in mobile communications [3].

In a conventional serial data system, the symbols are transmitted sequentially, with the frequency spectrum of each data symbol allowed to occupy the entire available bandwidth. Burst errors caused by fading result in the complete destruction of a series of adjacent symbols and the delay spread introduced by the channel limits the transmission rate in order to prevent intersymbol interference (ISI). The channel is selective in frequency.

In a parallel transmission system, several sequential streams of data are transmitted simultaneously, so that at any instant many data elements are being transmitted. In such a system, the spectrum of each individual symbol occupies only a small part of the whole available bandwidth. The total bandwidth is divided into N orthogonal subchannels, each of them is modulated by one symbol and they are all frequency multiplexed. A parallel approach has the advantage of spreading out a frequency selective fade over many symbols, which randomizes burst errors caused by fading.

In OFDM, a block of N serial symbols of duration T is converted into a block of N parallel symbols of duration Ts=NT, where the N carriers are placed at the frequencies:

$$f_k = f_c + k/Ts \qquad k=1,2,\ldots,N-1 \qquad (1)$$

A higher spectral efficiency can be achieved if the different subchannels are allowed to overlap. Orthogonality between them simplifies the separation process in the receiver. The values of N adopted in the simulations are 2K (N=2024 carriers) and 8K (N=8192 carriers) which are compliant with the dTTb proposal.

The symbol duration is longer which allows the effect of the delay spread of the channel to be reduced when $NT >> \sigma_T$, where σ_T is the rms value of the delay spread of the channel. The bandwidth occupied by each subchannel in an OFDM symbol will be small compared with the coherence bandwidth of the channel, so the channel is frequency non-selective.

The multiplexing and demultiplexing process can be accomplished easily using an inverse FFT in the transmitter and a FFT in the receiver [4]. This guarantees orthogonality and simplifies the design, allowing the construction of a totally digital modem. Figures 1 and 2 show a totally digital implementation of a OFDM transmitter and receiver respectively

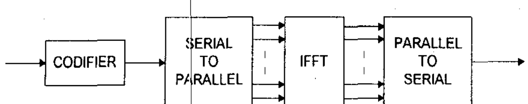

Figure 1. OFDM transmitter.

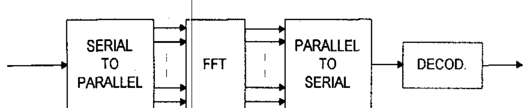

Figure 2. OFDM receiver.

The multipath characteristic of the channel spreads each OFDM symbol, which produces OFDM intersymbol interference. In order to avoid this effect, a temporal guard of duration T_g is added to each OFDM symbol, repeating the last part of the FFT and placing it at the end of the symbol. Thus, the characteristic of periodicity of the FFT is used. The OFDM symbol duration will be $T_{s'} = T_s + T_g$. ISI can be eliminated if the delay of the last echo is shorter than the guard interval duration, T_g. Therefore, the selection of T_g will depend on the channel characteristics, binary rate and the multilevel modulation scheme applied. In the simulations performed, a value of $T_g/T_s = 1/8$ has been adopted, which is compliant with the dTTb proposal for 2K and 8K systems.

A frequency guard is also added in order to avoid adjacent channel interference (analogue or digital channels). Frequency nulls are introduced into some subcarriers placed on both sides of the OFDM symbol. The selection of the frequency nulls will depend on the frequency band characteristics and occupation, and the adjacent channels' guard band. It will also depend on the number of carriers, N, used in the FFT. In the simulations performed, the values proposed for dTTb have been adopted.

The number of OFDM carriers, N, is a compromise between frequency and phase stability requirements and the capability of combating selective frequency fading.

3. OFDM IN NONLINEARITY.

RF power is as always a critical issue. The RF High Power Amplifier (HPA) is intended to be used as efficiently as possible. However, when a HPA is driven hard, i.e. at or near saturation, it exhibits nonlinear behaviour and distorts the multicarrier signal, degrading the system performance. The conflicting requirements of high power and signal distortion need to be balanced carefully. There is a trade off between the back-off (amplifier efficiency) and the maximum degradation allowed. A Solid State Power Amplifier (SSPA) is considered as a candidate for MVDS high power amplification.

Theoretically, the difference of peak-to-average power ratio between a multicarrier system and a single carrier system is a function of the number of carriers as:

$$\Delta(dB) = 10\log N \qquad (2)$$

where N is the number of carriers. When N=1000, the difference can be as large as 30dB. However, this theoretical value rarely occurs. Since the input data are well scrambled, the chances of reaching its maximum value are very low, especially when the constellation size is large [5].

OFDM signals can be treated as a series of independent and identically distributed modulated carriers. Therefore, it follows from the central limit theorem [6] that the OFDM signal distribution tends to be

Gaussian when the number of carriers, N, is large. Generally, when $N > 20$, which is the case for most OFDM systems, the distribution is very close to Gaussian.

The high peak-to-average power ratio of an OFDM signal makes it susceptible to nonlinear or clipping distortions, as the signal peaks may occasionally thrust into the saturation region of the power amplifier. The result is BER degradation and adjacent channel interference. Moreover, this nonlinear effect will depend on the multilevel modulation applied and will be greater than the single carrier equivalent system. In the presence of both nonlinear distortion and additive Gaussian noise, optimized output power back-off is needed to reduce the OFDM signal degradation. For this purpose, an OFDM system has been built using SPW simulator where the 2K and 8K systems have been simulated with QPSK and 16-QAM modulation schemes. The system performance has been characterized by means of the symbol error rate (SER) as a function of the signal to noise ratio (S/N) at the input of the sample and hold subsystem. The SER has been estimated using the Monte Carlo method.

4. SIMULATION RESULTS.

In order to validate the system, a simulation was executed without the amplifier so that the signal degradation would be as low as possible. The QPSK/OFDM and 16QAM/OFDM systems have been compared with the single carrier (SC) QPSK and 16QAM equivalent systems. Once the system was validated, the system performance was studied in the presence of the amplifier nonlinearity in order to evaluate the back-off that must be introduced to reduce degradation to the required minimum level. First, OFDM clipping distortion will be discussed with the aim of comparing and validating the results that will be obtained when the amplifier is used in the simulations. After that, the amplifier distortion will be considered.

4.1. EFFECT OF CLIPPING.

4.1.1. 16QAM/OFDM system.

The OFDM system block diagram used in the computer simulations is shown in figure 3:

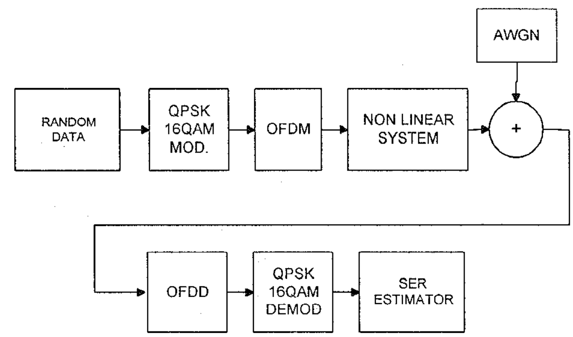

Figure 3. OFDM system block diagram.

The transmitter consists of a random binary source, a 16-QAM modulator using Gray encoding and the orthogonal frequency division multiplexer. The OFDM signal is implemented by means of an N-point inverse FFT, with N carriers. For the 8K system, $N=8192$ where the first 667 and the last 668 carriers are nulled as a frequency guard in order to avoid adjacent channel interference. For the 2K system, $N=2048$, where the first 171 and the last 172 carriers are nulled. Both systems have a temporal guard $T_g/T_s=1/8$ in order to avoid intersymbol interference, where the last 1024 and 256 samples of the FFT are repeated at the beginning of the OFDM block for the 8K and 2K systems respectively.

White Gaussian noise is added to the signal. In the receiver, the signal is Orthogonal Frequency Division Demultiplexed (OFDD) by an N-point FFT and 16-QAM demodulated. The SER is estimated by comparison between the transmitted and received constellations.

For comparison with the single carrier (SC) 16QAM system, the simulation is executed without the limiter so that the degradation will be as low as possible. Figure 4 compares the log(SER) curves versus the

(S/N) ratio obtained by simulation for the *OFDM* and SC systems.

It can be seen in the figure that the two curves are almost identical as was expected, though a variation of less than 0.8dB in (S/N) is observed due to the frequency guard interval used in the OFDM system, which results in a equivalent noise bandwidth reduction and, therefore, a slight improvement in SER performance. The curves for the 2K and 8K systems are virtually the same.

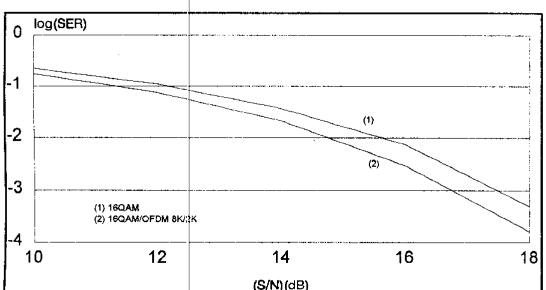

Figure 4. 16QAM/OFDM system. SER evaluation.

To study the clipping effect, a (S/N)=16dB has been used, which means a log(SER)=-2.54 without clipping. The back-off is defined as the ratio of the maximum clipping power to the input signal power (i.e. $BO=A^2/2\sigma^2$).

A 11.45dB peak-to-average power ratio was measured through simulations for the 2K and 8K systems. This shows the high variation of the OFDM signal as compared to the 3dB peak-to-average power ratio measured for the SC/16QAM signal. Both 2K and 8K systems show the same behaviour due to the Gaussian distribution of the OFDM signal when the number of carriers is large. Figure 5 shows the OFDM signal distribution obtained through simulation, where the Gaussian characteristic of the distribution can be clearly observed.

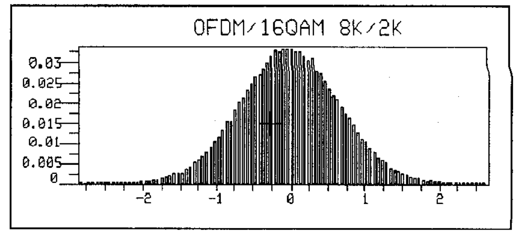

Figure 5. 16QAM/OFDM signal distribution.

The effects of limiter induced clipping noise on the SER performance of a 16QAM/OFDM signal is presented in figure 6, for a soft limiter whose transfer function is:

$$y = g(x) = \begin{cases} A & x \geq A \\ x & A \geq x \geq -A \\ -A & x \leq -A \end{cases} \qquad (3)$$

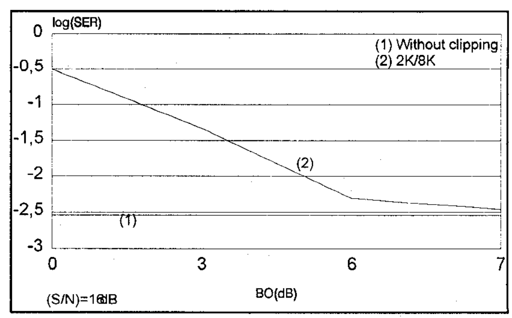

Figure 6. Effect of clipping on the SER performance of 16QAM/OFDM 2K/8K.

It can be seen that the same performance is obtained for the 2K and 8K systems and the SER degradation is negligible for BO=6dB (a log(SER) degradation of 0.23).

A SC/16QAM system was also evaluated through simulation and BO=3dB was concluded to be enough to allow the system performance to recover without any SER degradation.

4.1.2. QPSK/OFDM system.

The block diagram and the OFDM signal have the same characteristics as those described in the last section, but now the modulation scheme applied is QPSK.

For comparison with the SC/QPSK system, the simulation is executed without the clipping effect so that the degradation will be as low as possible. Figure 7 compares the log(SER) curves versus the (S/N) ratio for the OFDM and the SC system. It can be seen in the figure that the two curves are almost identical though a slight improvement is observed in the OFDM system because of the frequency guards (about 0.7dB in (S/N) ratio). The curves for the 2K and 8K systems are virtually the same.

To study the clipping effect, a (S/N)=9dB has been used, which results in a log(SER)=-2.32 without clipping. A 12dB peak-to-average power ratio was measured through simulation for the QPSK/OFDM signal. Both 2K and 8K systems show the same behaviour. This means a high variation of the OFDM signal versus the 0dB peak-to-average power ratio obtained for the equivalent SC system. Figure 8 shows the OFDM signal distribution for both the 2K and 8K systems; the Gaussian characteristic of the distribution can be clearly seen.

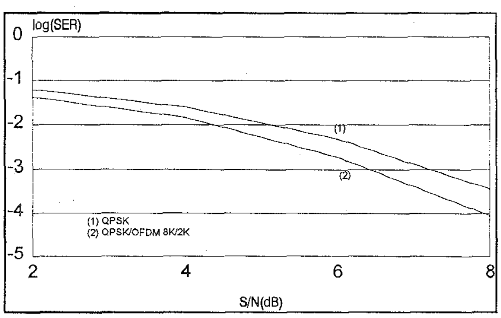

Figure 7. QPSK/OFDM system. SER evaluation.

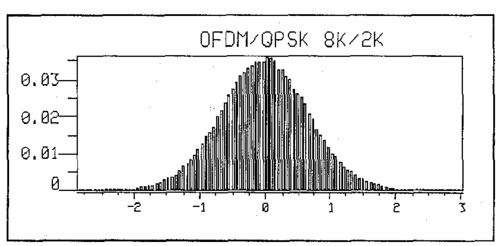

Figure 8. QPSK/OFDM signal distribution.

Figure 9 shows the effect of clipping on the SER performance of a QPSK/OFDM signal for both 2K and 8K systems, for a soft limiter. It can be seen that the same curve is obtained for the 2K and 8K systems and the SER degradation is low for 3dB BO (a log(SER) degradation of 0.59).

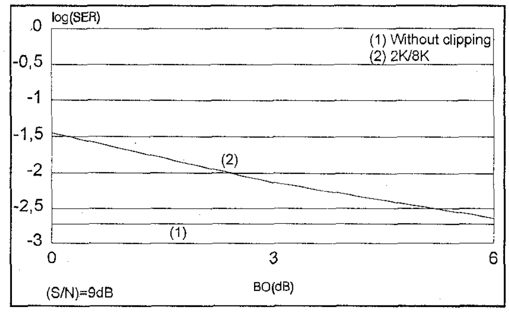

Figure 9. Effect of clippling on the SER performance of QPSK/OFDM 2K/8K.

Comparison of these results with the ones obtained in the 16QAM/OFDM simulations shows that the QPSK/OFDM signal is less sensitive to the clipping effect. This is a consequence of the lower amplitude of the constellation states.

A SC/QPSK system was also evaluated through simulation and it was concluded that it is not necessary to introduce back-off in order to reduce the clipping effect, due to the low average-to-peak power ratio.

4.2. EFFECT OF THE RF AMPLIFIER.

4.2.1. 16QAM/OFDM system.

The nonlinear behaviour of the RF amplifier has also been studied. The low pass equivalent or complex envelope concept has been applied in the simulations. If the input signal is of the form $A(t)e^{j\theta(t)}$ (an amplitude and/or phase modulated signal), the power amplifier output signal can be expressed as:

$$y(t) = f[A(t)]e^{j(\theta(t)+g[A(t)])} \qquad (4)$$

where f[A] is the AM/AM characteristic of the amplifier and g[A] is the

AM/PM characteristic of the amplifier. The simulation model is shown in figure 10.

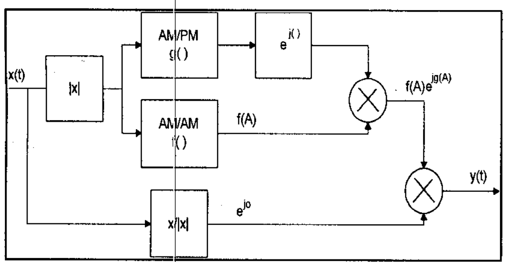

Figure 10. Simulation model of the nonlinearity.

The phase behaviour of a SSPA can be considered linear enough to neglect its effect on the signal. Therefore, only amplitude distortion has been taken into account, and it has been modeled in an analytical way based on the small signal gain, the 1dB compression point and the third order interception point of the amplifier.

To study the amplifier effect, a 0dBm OFDM signal power and a (S/N)=16dB have been used, which means log(SER)=-2.54 without the amplifier effect. The amplifier has a 10dB gain and a 35dBm third order interception point. Its compression point has been varied to analyse the effect of back-off on the OFDM signal. The SER ratio has been estimated by means of the Monte Carlo method.

Figure 11 shows the SER degradation as a function of the BO for (S/N)=16dB and PI_3=35dBm. As can be seen in the figure, 2K and 8K systems show a virtually indentical behaviour and a 6dB BO is needed in order to recover the system performance with a log(SER) degradation of 0.13. These results are compliant with the ones obtained in the clipping effect study.

Figure 12 shows the SER performance as a function of BO, parametrized by the third order interception point of the amplifier. Greater degradation is observed when the third order interception point approaches the 1dB compression point.

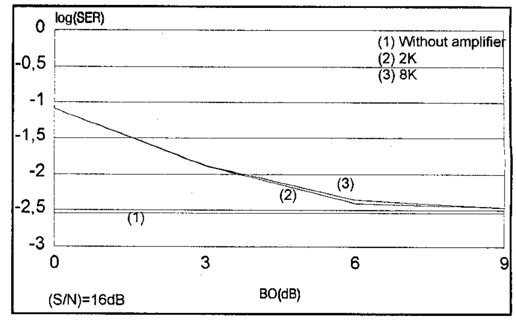

Figure 11. Amplifier effect on the SER performance of 16QAM/OFDM 2K/8K.

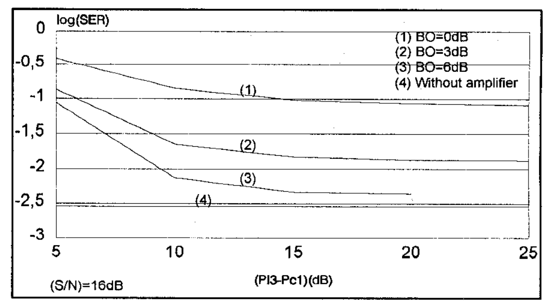

Figure 12. 16QAM/OFDM signal in amplifier nonlinearity. PI_3 sweepping.

A SC/16QAM system has also been simulated. Figure 13 shows the SER performance versus the Eb/No ratio for a SC/16QAM system. The BO is varied to evaluate the effect on SER performance and square root raised cosine filters with roll-off equal to 0.35 (35%) have been used in transmission and reception. As can be seen in the figure, the SER degradation is negligible for 3dB BO.

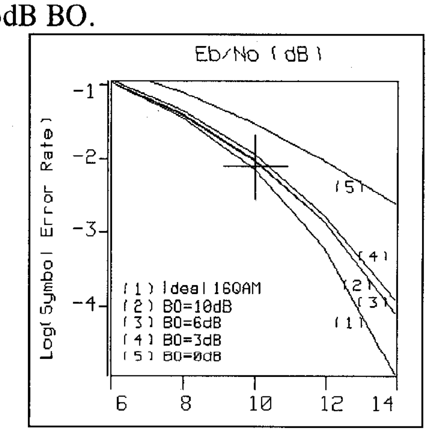

Figure 13. SC/16QAM system in nonlinearity. SER evaluation.

4.2.2. QPSK/OFDM system.

In this case, a 0dBm OFDM signal power has been used and a (S/N)=9dB, which means log(SER)=-2.72 without the amplifier effect. The amplifier has a 10dB gain and a 35dBm third order interception point. The compression point is varied to observe the BO effect on the OFDM signal.

Figure 14 shows the SER performance as a function of the BO for (S/N)=9dB and PI_3=35dBm. As can be seen in the figure, 2K and 8K systems show the same behaviour and a 3dB BO is needed in order to recover the system performance with a log(SER) degradation of 0.16. These results are compliant with the ones obtained in the clipping effect study. Comparison of these results with the ones obtained in the 16QAM/OFDM simulations shows that the QPSK modulation scheme is less sensitive to amplifier nonlinearity as a consequence of the lower amplitude of the constellation states.

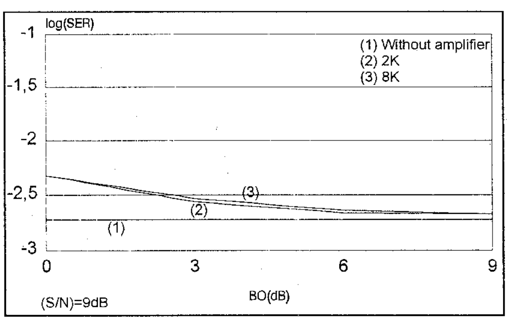

Figure 14. Amplifier effect on the SER performance of QPSK/OFDM 2K/8K.

Figure 15 shows the SER performance as a function of BO, parametrized by the third order interception point of the amplifier. Greater degradation is observed when the third order interception point approaches the 1dB compression point. However, this degradation is less severe than in the 16QAM/OFDM system, which shows the strength of the QPSK modulation scheme in the presence of nonlinear systems.

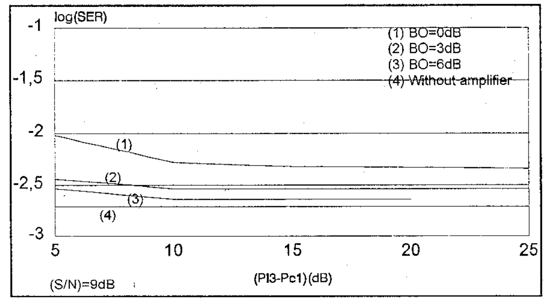

Figure 15. QPSK/OFDM signal in amplifier nonlinearity. PI_3 sweepping.

A SC/QPSK system has also been simulated. Figure 16 shows the SER performance versus the Eb/No ratio for a SC/QPSK system. The BO is varied to evaluate the effect on SER performance and square root raised cosine filters with roll-off equal to 0.35 (35%) are used in transmission and reception. As can be seen in the figure, the SER degradation is negligible without any back-off.

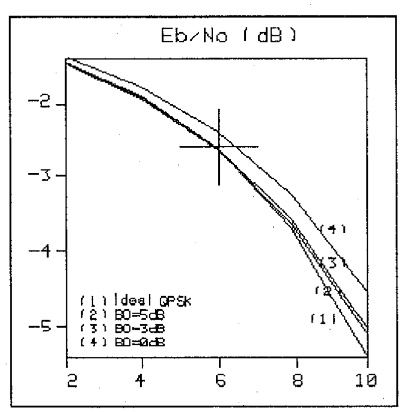

Figure 16. SC/QPSK system in nonlinearity. SER performance

5. CONCLUSIONS.

The activities of the current European RACE and ACTS projects have led to an increasing interest in OFDM (Orthogonal Frequency Division Multiplexing) as a means of combating impulsive noise and multipath effects and making fuller use of the available bandwidth of the system.

The high peak-to-average power ratio of the OFDM signal makes it susceptible to nonlinear or clipping distortions as the signal peaks may occasionally thrust into the saturation region of the power amplifier. The result is a performance degradation which requires optimization of the back-off in order to balance carefully the conflicting requirements of power efficiency and signal distortion.

The results obtained by means of computer simulations show SER performance degradation as a function of clipping and nonlinear distortions in 16QAM/OFDM and QPSK/OFDM systems. 2K and 8K systems show almost identical behaviours due to the same Gaussian distribution of an OFDM signal when the number of carriers is large enough (N > 20). However, the behaviour of the OFDM system depends on the modulation scheme applied. When 16QAM modulation is used, a 6dB back-off is needed to make the SER degradation negligible, while for QPSK modulation a 3dB BO is enough. In both cases, the degradation is greater than for single carrier systems (3dB in the best case).

REFERENCES

[1] SPW (Signal Processing WorkSystem), Alta Group. **3.1**. Version.

[2] dTTb Module 3, 'System Specification for the Second dTTb Demonstrator', **dTTb/M3/284**. Feb. 1996.

[3] Leonard J. Cimini, 'Analysis and Simulation of a Digital Mobile Channel Using Orthogonal Frequency Division Multiplexing'. *IEEE Transactions on Communications*, vol. **COM-33**. N° 7. July 1985.

[4] S.B. Weinstein, P.M. Ebert, 'Data Transmission by Frecuency-Division Multiplexing Using the Discrete Fourier Transform'. *IEEE Transactions on Communication Technology*, vol. N° **5**. October 1971.

[5] Yiyan Wu and William Y.Zou, 'Performance Simulation of COFDM for TV Broadcast Application'. *SMPTE Journal*. May 1995.

[6] Yiyan Wu and William Y.Zou, 'COFDM: An Overview'. *IEEE Transactions on Broadcasting*, vol **41**. March 1995.

Biographies

Jose Luís García García (M'85) was born in Zaragoza, Spain, in 1938. He received an M.S.E degree from the University of Zaragoza in 1964 and a PhD from the University of Valladolid, Spain, in 1971. From 1966 to 1973 he was Associate Professor at the University of Valladolid where he worked on analog simulation of systems and the generation of pseudo-random signals. In 1973 he became professor of Electronics Engineering of the Department of Electronics of the University of Cantabria in Santander (SPAIN) where he has been dean of the Telecommunications Engineering School and head of Department. At present he is the head of the Department of Communications Engineering. He teaches Radiocommunication Systems and Satellite Communications. He has worked in microwave and millimetric wave systems and components for mobile, radiolinks and satellite communications. His current research interests include broadcasting of digital TV through satellite and SMATV-DTM systems; wireless CDMA-SS for indoor applications; low speed CDMA satellite communications and cellular access to broadband services and interactive television at millimetric waves. He is a member of the Committee of the E-12 professional group of the IEEE.

Ana García Armada was born in Santiago de Compostela on 17 June, 1970. She received a degree in Telecommunications Engineering from the ETSIT, Technical University of Madrid in July 1994. Since November 1994 she has been working on Simulation and Rapid Prototyping of the European Digital TV Terrestrial Broadcasting System (dTTb) based on COFDM signals as a PhD student in the same University. She collaborated in European RACE projects and worked in TIDSA and the European Space Agency-ESTEC during the final years of her undergraduate studies.

Sergio Merchán González was born in Burgos (SPAIN) on 2 September, 1973. In 1995 he joined the Department of Communications Engineering of the University of Cantabria where he collaborated in a European RACE project, DIGISMATV. He was awarded a degree in Telecommunications Engineering by the University of Cantabria in 1996. Since October 1996, as a PhD student in the same University, he has been participating in another European project, CABSINET, where he is defining and simulating a digital cellular access network to broadband interactive services following the DVB-MS standard. He is member of the IEEE.