Advanced OFDM-CDMA HF modem with self-interference cancellation

Conference Paper · November 2003

DOI: 10.1109/MILCOM.2003.1290133 · Source: IEEE Xplore

7 authors, including:

Ivana Raos
ASSIA Inc.
50 PUBLICATIONS **161** CITATIONS
SEE PROFILE

Ivan A. Perez-Alvarez
Universidad de Las Palmas de Gran Canaria
50 PUBLICATIONS **170** CITATIONS
SEE PROFILE

Santiago Zazo
Universidad Politécnica de Madrid
163 PUBLICATIONS **1,109** CITATIONS
SEE PROFILE

E. Mendieta-Otero
Universidad de Las Palmas de Gran Canaria
13 PUBLICATIONS **49** CITATIONS
SEE PROFILE

ADVANCED OFDM-CDMA HF MODEM WITH SELF-INTERFERENCE CANCELLATION

I. Raos[†], A. Del Cacho[†], I. Pérez-Álvarez, S. Zazo[†], E. Mendieta-Otero, H. Santana-Sosa, J.M. Páez-Borrallo[†]

Dpto de Señales y Comunicaciones. Universidad de Las Palmas de Gran Canaria. Spain
[†]ETS Ingenieros de Telecomunicación. Universidad Politécnica de Madrid. Spain
Phone: +34-91 5495700 ext 225, e-mail: ivana@gaps.ssr.upm.es

ABSTRACT

Performance of a modem designed for HF communications is presented in this contribution. The aim was to attain the real time communication for interactive voice transmission. Therefore, powerful coding for error protection and long interleaving was not permitted. Frequency selective HF channel was converted into a set of frequency flat channels with MultiCarrier modulation, Orthogonal Frequency Division Multiplex (OFDM). Spread Spectrum Technique (SST) was applied to improve modem's performance. This technique takes advantage of frequency diversity, as one symbol is transmitted (spreaded) over larger number of subcarriers (N), and more symbols (N) are transmitted simultaneously. Use of SS techniques permits us to perform advanced signal processing in receiver and further enhance modem's performance. We applied Multi User Detector (MUD) in receiver, denoting as "virtual users" the symbols transmitted simultaneously with different spreading codes. For data transmission, when delay is not restricted, coding and interleaving can be incorporated, improving drastically the performance.

INTRODUCTION

Communication in High Frequency (HF) band is not considered to be reliable, due to channel's great variations and highly dispersive characteristics, frequency selectivity, Doppler spread and multipath propagation. Briefly, it can be stated that all inconveniences of wireless channel are present, making this channel a very hostile environment.

Digital signal processing tools made possible more reliable transmission over wireless channels; multicarrier modulation, specifically Orthogonal Frequency Division Multiplex (OFDM), is an appropriate approach for combating those wireless channel's characteristics.

In this contribution punctual design points used in presented HF modem will be described. OFDM is applied, and Code Division Multiple Access (CDMA) technique used makes possible to get advantage of channel's frequency diversity. Convenient receiver design for this type of modulation is presented as well. With Reed-Solomon channel coding possible modem's useful data rates are approximately 2400 and 3600 bps, and digital voice can be transmitted interactively. [1] [2]

However, when interactivity is not the primer goal, the combination of long interleaving and more powerful channel coding make possible performance improvement. Convolutional code was applied, and it was included in Interference Cancellation loop. Preliminary computer simulations demonstrate the advantage of this added system complexity in BER improvement.

MULTICARRIER MODULATIONS FOR FREQUENCY SELECTIVE CHANNELS

Wideband wireless channels are usually frequency selective, meaning that channel affects signals at different frequencies in a different manner. This requires complex equalisers for single carrier modulations. Multicarrier modulation schemes were proposed a long time ago to combat this obstacle, but its implementation was made possible just recently with digital signal processing methods. The idea is quite simple, yet very effective to avoid complex receivers and to provide more reliable communication. By sending in parallel manner a set of narrowband signals with bandwidth narrow enough, channel frequency characteristic can be approximated as flat in each signal bandwidth, and each signal will experience flat fading. This modulation leads to simple channel equalisation in frequency domain, as it consists of one complex coefficient per subcarrier that compensates channel's influence. OFDM is single user multicarrier modulation based on specific frequency separation of carriers modulated with different signals. If this distance equals the inverse of the symbol duration, orthogonality between different signals is achieved.

However, frequency selectivity reflects in time dispersion as well. Additional benefit of OFDM is that by sending narrowband signals the signals' duration is larger and channel's dispersion affects them less than smaller, single carrier signals. Dispersion is usually combated in one of two existing approaches: by leaving intervals between symbols without transmitting, or by adding cyclic prefix. The former approach converts linear convolution into a circular one, permitting simple receivers, while the first one guarantees channel without zeros on unit circle.[3] Both of these techniques lead to efficiency loss; however, as mentioned previously, it is smaller than in case of single carrier modulation, and it results in much simplified signal processing at receiver.

HF CHANNEL SPECIFIC MODEM PARAMETERS

In HF band, signal is transmitted via ionospheric reflections, resulting in dispersive, frequency selective channel. Therefore, OFDM modulation is performed.

CCIR [4] chose a set of representative parameters for a two rays scenario with independent fading characteristic. Values of the time dispersion and Doppler spread are specified for 3 channel's types; the Good, Moderate and Poor channel. However, in our analysis, aeronautical channel considered in the Standard and Recommended Practices (SARPs) [5] is included as well. Performance of different approaches is tested fixing these characteristics modelling each channel with tapped delay line.

The design of the modem was performed to get satisfactory performance in terms of Error Probability and latency for these channel parameters. Compromise between efficiency loss due to CP and OFDM symbol duration necessary to consider time invariant channel; as well as distance between subcarriers that will not be deteriored a lot with Doppler spread, was intended to be found. All those parameters were studied for "the worst case channel" (channel with time spread 2ms and Doppler frequency 2Hz) as in the other channels those restrictions are looser.

Conclusion was reached that CP length of $T_{PC}=3.3\ ms$ eliminates completely the interference between OFDM symbols even for the testing channel with the time spreading of 2 ms with a probability of over 80%. This choice of CP length and OFDM symbols results in their relation of about 13%, remaining within standard limits. Including CP length, total duration is around 30 ms (26ms+3.3ms), and even the worst case channel can be considered static in one OFDM symbol of this duration.

OFDM-CDMA DESIGN

The simplified multiplicative model of one OFDM symbol transmission, assuming that the frequency offset has been corrected during the training period, and also no ISI, thanks to sufficiently long CP, is as follows:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \qquad (1)$$

where **x** (dimension *N*x1) represensents symbols transmitted by different subcarriers, **H** (*N*x*N)* is a diagonal matrix whose diagonal entries are the complex attenuation factors associated to the corresponding frequency transmissions, **n** is vector with white gaussian noise samples, and **y** *N*x1 is the received vector.

Frequency selective channel is converted into a set of flat fading channels, and symbol transmitted on one subcarrier will be affected only by one complex channel coefficient. This leads to simple equalisers consisting of one coefficient per each subcarrier.

Inconvenience of this modulation can be observed easily in the figure 1:

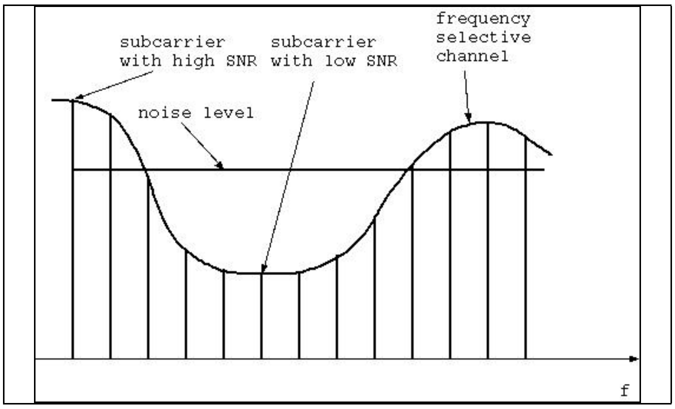

Figure 1: Frequency selective channel sketch

In the given bandwidth, noise level is constant, but Signal-to-Noise ratio (SNR) will vary depending on the channel's coefficient on each subcarrier. Therefore, if symbols are transmitted on "good" subcarrier (high SNR), it will have satisfactory error performance; on the other hand, symbols transmitted on "bad" subcarriers (low SNR) that corresponds to channel's nulls will suffer performance degradation.

Channel coding is one of the manners to combat this effect of channel's frequency selectivity, as channel codes for error correction average system performances. If interleaving is performed in frequency domain, "good" signals should provide enough information at the receiver to detect and correct "bad" symbols' errors. The other point of view is to perform interleaving in time domain, per subcarrier. If done so, interleaver size should be larger than channel's fades.

Channel codes require both redundancy and latency: additional bits will result in smaller data rates, and time necessary for interleaving, encoding/decoding will limit data types that can be transmitted. However, with this approach, improved performance necessary for data transmission is obtained.

In modem design we are proposing, the principle of CDMA is applied; all symbols are spread over all available subcarriers. This approach averages channel characteristic per one OFDM symbol. When compared to channel codes, it can be seen that this averaging does not require any additional data, nor results in increased latency.

The transmitted data are now represented by the following equation:

$$\mathbf{y} = \mathbf{HCx} + \mathbf{n} \qquad (2)$$

where **C** is an orthogonal transformation matrix based on one technique whose fundamental background are MC-CDMA (MultiCarrier CDMA) techniques. If the number of carriers is a power of 2, Hadamard codes are usually chosen due to their simplicity; however, any other orthogonal codes' matrix will do.

MC-CDMA is a multiple access technique based on the combination of OFDM and CDMA principles. Different users share all available subcarriers, and orthogonal codes are assigned to them enabling receiver to separate their symbols.

This approach can be applied in the modem's design although there is no multiple access in this case. However, if each one of N symbols transmitted in one OFDM symbol is denoted as "virtual" user, a kind of multiple access is achieved. This permit the receiver's design as if we were using it in a downlink MC-CDMA channel, and as if all users' symbols are to be detected; that is, MultiUser Detector (MUD) should be applied.

Parallel Interference Canceller (PIC) scheme was chosen, as it has better performances in a perfect power control case when compared to lineal MUD [1]. As we are dealing with "virtual" users, they are all assigned the same power in the same transmitter and power control is perfect.

Simplified scheme of the PIC applied to detect symbols of different "virtual" users is depicted in figure 2. PIC is an iterative detector that estimates the received symbols in each substream and substracts them from the received vector to perform a better estimate.

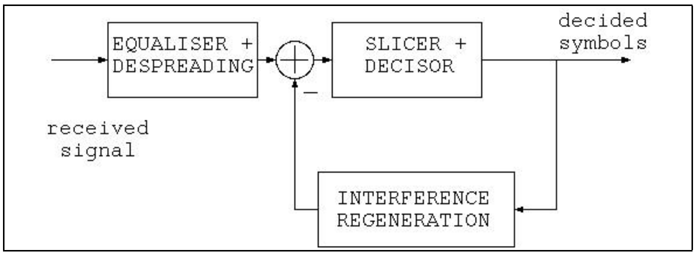

Figure 2: Sketch of PIC

First block in this figure shows that channel's equalisation must be doned at the very beginning of the process. In practice, channel estimation allows us a simple design for the equalization matrix **G** using several criteria:

$$\begin{aligned} &\mathbf{G} = \hat{\mathbf{H}}^{-1} && \text{Zero} - \text{Forcing}\,(\text{ZF}) \\ &\mathbf{G} = \hat{\mathbf{H}}^{H}\left|\hat{\mathbf{H}}\right|^{-1} && \text{Equal Gain Combining}\,(\text{EGC}) \\ &\mathbf{G} = \hat{\mathbf{H}}^{H}\left|\hat{\mathbf{H}}\right|^{-2} && \text{Maximum Ratio Combining}\,(\text{MRC}) \end{aligned} \qquad (3)$$

where $(*)^H$ stands for hermiric transpose of matrix.

A ZF criterion eliminates Multi("virtual")User Interference (MvUI) on the cost of noise enhancement. This is not adequate for PIC as interference is already removed, and noise cannot be minimised with it. Therefore, analysis was conducted to compare system performances with EGC and MRC equalisation. EGC showed better performance in this application, when PIC is applied. However, ZF equalisation turns out to be the most convenient if PIC is not used, as other criteria cannot cope with MvUI.

After despreading, the signal at slicer can be represented as:

$$\mathbf{s} = \mathbf{C}^{H}\mathbf{GHCx} + \mathbf{C}^{H}\mathbf{Gn} \qquad (4)$$

After decision on sent symbols, an iterative interference regeneration process is conducted. Mathematically, the k^{th} iteration can be described with:

$$\left(\frac{tr\{\mathbf{GH}\}}{N}\mathbf{I} - \mathbf{C}^{H}\mathbf{GHC} \right)\mathbf{x}_{k-1} \qquad (5)$$

where $tr\{*\}$ stands for trace operator.

This interference regenerator uses estimates of N symbols transmitted in one OFDM symbol ($\mathbf{x}_{k-1}$) to regenerate InterCarrier Interference (ICI). This interference appears due to inexact channel estimation. This is easily understandable if we pay attention to figure 1 again. Channels characteristic on subcarriers with low SNR will not be estimated as well as on those with high SNR. Degradation due to this “miss-estimation” is intented to be minimized in PIC loop.

SMART PIC FOR OFDM-CDMA

When interactivity is not required, but system performance in terms of BER is important (as it is in case of data transmission), channel coding is welcomed. Instead of using just Reed- Solomon codes, more powerful convolutional codes are applied. However, their performance is highly dependent on interleaving. If there is a stream of too much noise corrupted contiguous symbols, Viterbi decoder will have greater BER. Therefore, interleaving is the necessity for these types of codes.

With multiple virtual users and PIC, the most convenient way for signals coding is per virtual user. In this case, decoding can be performed within the canceller loop, and better performances are obtained. Interleaver size should be great enough in order to outcome channels fades.

This scheme, in which different virtual users are encoded separately with channel codes enabling decoding in each loop of PIC, is denoted smart PIC. It obtains better performance since the interference estimation has a higher realibility. In fact when the channel decoding is performed inside the cancellation loop this detector outperforms the maximum likelihood estimator [7].

When the channel decoding is performed inside the cancellation loop, the symbol estimates must be reencoded and reinterleaved prior to the cancellation. If convolutional encoding is used, soft estimates of the symbols are preferred in order to obtain better decoding performance.

RESULTS ANALYSIS

Some aspects described in this contribution were simulated in this section. In the figure 3, performance of PIC in moderate channel specified by [4] is shown. Advantage of using PIC instead of simple equalisation at receiver becomes obvious at higher SNR’s. This is easily justified as PIC is a type of decision-directed scheme, and at high SNR error propagation effect will have less influence than at low SNR’s.

As this is an iterative method, different number of iteration was conducted to compare obtained improvement. It was observed that with a small number of iterations, 3, significant improvement is obtained. However, further increment of the number of loops does not lead to high performance enhancement, as is shown in figure 3.

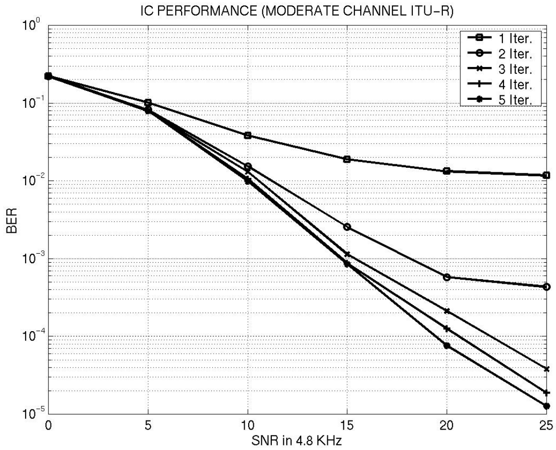

Figure 3: Influence of number of iteration in PIC loop in modem’s performance

Scheme with 16 aubcarriers and QPSK modulation has been analized via simulation in Rayleigh independent fading channel. A convolutional code with rate ½ and constraint length 7 has been used for channel coding. Three bits soft estimates of the symbols are used to enhance the channel decoder. Equalization was performed with MMSE equalizer. In the figure 4, performances of different receivers for this scenario are presented in terms of BER.

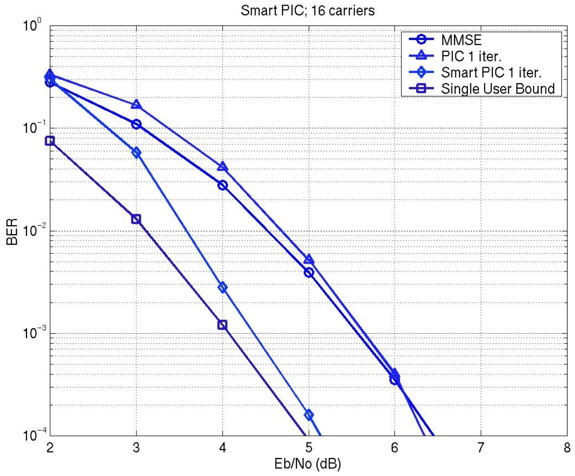

Figure 4: PIC performance (16 carriers)

At low E_b/N_o the conventional PIC performance is worse than the MMSE detector since there are a lot of errors in the uncoded estimation of the interference. It can be seen that at higher values (≈6dB) the PIC begins to outperform the MMSE detector. The smart PIC, which includes the channel decoding inside the cancellation loop, outperforms both of them obtaining results very close to the single user bound with only one iteration.

Aditional tests, signals samples and digital voice samples with differents channels can be founded in the anonymous ftp server ftp://gic.dsc.ulpgc.es/interactiveHFvoice .

CONCLUSIONS AND FUTURE RESEARCH LINES

Some punctual aspects of HF modem's design were addressed in this contribution. It is shown that multicarrier modulation is the one adequate for frequency selective HF channel and some relevant design parameters were obtained. Special attention was dedicated to the idea and analysis of OFDM-CDMA method. It is convenient for interactive modem design as it does not add latency like interleaving and channel codes schemes, but it does take advantage of frequency diversity. Advanced signal processing at receiver was presented, with Multi User Detectors, specifically Parallel Interference Canceller.

If data transmission is addressed as a goal, interleaving and channel coding will improve performance although interactivity is lost. However, in data transmission, performance in terms BER is more important; modem including this possibility in design can be used both for data and interactive digital voice transmission. In the proposed modem design coding is performed per virtual user, still making possible the use of Interference Canceller at receiver.
Smart PIC should be analysed in more realistic environment in order to obtain more reliable results. Presented preliminary simulations demonstrate its gain and give a good feeling about its capability.

ACKNOWLEDGEMENT

The work presented in this contribution was supported by AENA (Spanish Airports and Air Navigation) projects 00/49 and 00/50, and partly by projects 07T/0032/2000, IST-2001-32620, TIC200-1395-C02-02 and TIC2002-04569-C02-02.

REFERENCES

[1] S. Zazo, F. Bader, J.M. Páez-Borrallo *"Spread Spectrum OFDM Modem for HF Voice-Band Link Over Fading Channels*" European Transactions on Telecommunications, Vol 11, No.6, November/December 2000

[2] I. Pérez-Álvarez et *al "Interactive Digital Voice Over HF*" Proceedings IEE HF Radio Systems and Techniques, June 2003, Bath, UK.

[3] Z. Wang, G. B. Giannakis "Wireless Multicarrier Communications: Where Fourier Meets Shannon" IEEE Signal processing Magazine, May 2000, pp. 29-48

[4] CCIR, Rc 520-1: "On the Use of Ionospheric Channel Simulators in Decametric Waves", 1978-1982

[5] SARPs for HFDL. Validation by AMCP-Memo/8, September 1998, Montreal, Canada

[6] G. Xue, J. Weng, T. Le-Ngoc, S. Tahar "*Miltiuser Detection Tecniques: An Overview*" Technical report, Department of Electrical and Computer Engineering, Concordia University, Canada, Dec., 1998.

[7] Stefan Kaiser, "Multi-Carrier CDMA Mobile Radio Systems. Analysis and Optimization of Detection, Decoding, and Channel Estimation", Ph.D. Thesis, Dusseldorf, Germany 1998