MULTI-CARRIER TECHNIQUES PERFORMANCE ON IONOSPHERIC CHANNEL FOR DELAY-SENSITIVE APPLICATIONS

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ABSTRACT

Multi-carrier modulations are widely employed in HF communications, and particularly OFDM, mainly because their ease of generation by means of DFT and also their appealing properties that can turn a selective fading channel into a set of flat channels. In order to cope with deep nulls in the channel traditional approach has been the use of channel coding and interleaving, thus causing an increase in communication delay. For delay-sensitive applications, spreading schemes over OFDM, such as OFDM-CDM can be applied. If CSI is known at transmitter, system performance can be improved by BER-optimum power loading and channel matrix SVD decomposition of OFDM-CDM signal. These techniques are well suited to delay-sensitive applications as they incur in no further delays.

I. INTRODUCTION

HF communications through ionospheric channel have been traditionally carried out by use of single-carrier modulations. The channel presents selective fading, which means that some parts of the band suffer different magnitude and phase modifications than other parts. The bandwidth where fading can be considered as flat is known as channel frequency coherence. This selective fading can be caused by a number of effects, such as multipath.

Ionospheric channel is also time varying, causing deep nulls that in turn, can cause burst errors. Duration of these errors is giving by channel time coherence, whose inverse is known as doppler spread. This effect can be caused by the changing nature of the channel.

A. Multi-carrier Modulations

In order to cope with selective fading, nowadays HF communications make extended use of multi-carrier modulations. These kind of modulations make use of more than one carrier to transmit data. Each carrier is modulated at a lesser rate that would be necessary to transmit the joint information by way of single-carrier modulations. Thus, bandwidth channel can be considered as flat for each sub-carrier.

Among multi-carrier techniques, the most extended is Orthogonal Frequency Division Multiplex (OFDM), mainly because its ease of generation by means of Discrete Fourier Transform (DFT), and its appealing properties. Thanks to orthogonality between sub-carriers, Intercarrier Interference (ICI) can be avoided, while the use of cyclic pre- and post-fixes eliminates Intersymbol Interference (ISI). Conjunction of sub-carriers bandwidth below frequency coherence bandwidth and cyclic prefixes warranty availability of a strictly flat equivalent channel.

However, in presence of deep nulls, one or more OFDM sub-carriers can be too attenuated as to recover information. Different techniques are available to cope with deep nulls destructive effects, depending on characteristics imposed by the communication system to be used. Classical techniques deal with this problem without Channel State Information (CSI), mainly through channel coding and interleaving. These techniques are not well suited to sensitive-delay applications. In this case, if CSI is available, system performance can be increased without delay penalty.

II. CODING TECHNIQUES WITHOUT CHANNEL SATE INFORMATION

Traditional techniques helping to avoid information loss are channel coding and interleaving, widely known as COFDM (Coded OFDM). Channel coding, such as convolutional coding, adds redundancy, turning bits to be transmitted into a higher number of symbols. Interleaving assigns these symbols to different sub-carriers apart enough, both in frequency and time. This accounts for both time and frequency diversity in HF channel.

The longer interleaving depth is, the longer error burst duration the system will be able to cope with. But as interleaving depth grows, so does communication delay. Thus, interleaving depth is a compromise between communication delay and target Bit Error Rate (BER), and as such it depends on both channel nature and application the system is designed for [1].

Another way to avoid deep null effects while keeping delay at minimum is to apply spreading schemes over OFDM

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modulation, resulting in OFDM Code Division Multiplex (OFDM-CDM) [2]. Transmitted symbols are distributed over all sub-carriers, or over a subset of them, making use of orthogonal codes, usually Walsh-Hadamard codes. Each sub-carrier transports only part of a symbol, so that even if it suffers a disastrous attenuation, such symbol may possible be recovered by joint contribution of surviving sub-carriers. Multiple Access Interference (MAI) is a spreading disadvantage, usually requiring Multiple User Detectors (MUD) at receiver [3][4].

III. PRECODING BASED ON CHANNEL STATE INFORMATION

If information about channel state is known at transmitter, it is possible to precode the signal to be transmitted in order to achieve channel capacity and/or BER performance. Contrary to solely detection-based methods CSI requires transmitter processing but not necessarily at receiver.

Regardless the way channel state is acquired, time between acquisitions by the transmitter must be short relative to channel time coherence. Under real conditions, the system must cope with imperfect CSI at receiver and/or transmitter. These imperfections can be modeled as random perturbations on the channel matrix available to transmitter and receiver to precode. In this paper only perfect CSI will be taken under consideration, as an upper bound of what CSI can provide relative to BER performance.

In order to take advantage of CSI at transmitter, different schemes can be applied over signals to be transmitted. The simplest one is based on waterfilling principles, where total available transmitting power is distributed among sub-carriers in order to fulfill some goal such as mutual information maximization or BER minimization.

In the presence of MAI, as in OFDM-CDM transmissions, when channel matrix can no longer be considered as diagonal, a more robust CSI scheme than that of power loading is to be applied. This technique, based on the Singular Value Decomposition (SVD) of channel matrix, corresponds to one of the simplest methods for joint processing.

A. Power Loading

As stated previously, when CSI is known at transmitter it is possible to optimally distribute available transmit power among sub-carriers. Different algorithms based on the waterfilling principle are available to choose the optimum power distribution based on some criterion [5]. The most common are maximization of mutual information, in order to achieve channel efficiency, and BER minimization. These techniques apply when communication is assumed to be carried out over independent channels, such in the case of plain OFDM or OFDM-CDM plus SVD decomposition transmissions. The latter will be explained below.

In this paper the optimum power distribution will be based on BER minimization rather than mutual information maximization, as we wish to transmit a fixed amount of information over the channel with the highest possible reliability.

B. Singular Value Decomposition

Channel matrix SVD decomposition is a straightforward transmission scheme that allows to take advantage of channel knowledge jointly both at transmitter and receiver (SVD) [6]. Calling $\boldsymbol{H}_{eq}$ channel equivalent matrix for reasons that will become apparent later on. $p \times q$ $\boldsymbol{H}_{eq}$ matrix can be obtained as a product of three matrices $\boldsymbol{U}$, $\boldsymbol{\Sigma}$ and $\boldsymbol{V}$ as,

$$\boldsymbol{H}_{eq} = \boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{\mathrm{H}}, \tag{1}$$

with $\boldsymbol{\Sigma}$ $p \times q$ diagonal of singular values, and $\boldsymbol{U}$ and $\boldsymbol{V}$ $p \times p$ and $q \times q$ unitary matrices respectively.

If transmit vector is $\boldsymbol{s}$, transmitter processing is given by

$$\boldsymbol{x} = \boldsymbol{V}\boldsymbol{s}, \tag{2}$$

where $\boldsymbol{x}$ is the actual transmitted signal. If received signal is $\boldsymbol{y} = \boldsymbol{H}_{eq}x + n$, proper receiver processing in order to obtain $\hat{\boldsymbol{s}}$ as signal estimation for $\boldsymbol{s}$ is given by

$$\hat{\boldsymbol{s}} = (\boldsymbol{\Sigma}^{\mathrm{H}}\boldsymbol{\Sigma})^{-1}\boldsymbol{\Sigma}^{\mathrm{H}}\boldsymbol{U}^{\mathrm{H}}\boldsymbol{y}, \tag{3}$$

which yields

$$\begin{aligned}\hat{\boldsymbol{s}} &= (\boldsymbol{\Sigma}^{H}\boldsymbol{\Sigma})^{-1}\boldsymbol{\Sigma}^{H}\boldsymbol{U}^{H}(\boldsymbol{H}_{eq}\boldsymbol{x} + \boldsymbol{n}) \\ &= (\boldsymbol{\Sigma}^{H}\boldsymbol{\Sigma})^{-1}\boldsymbol{\Sigma}^{H}\boldsymbol{U}^{H}\boldsymbol{U}\boldsymbol{\Sigma}\boldsymbol{V}^{H}\boldsymbol{V}\boldsymbol{s} + (\boldsymbol{\Sigma}^{H}\boldsymbol{\Sigma})^{-1}\boldsymbol{\Sigma}^{H}\boldsymbol{U}^{H}\boldsymbol{n} \\ &\triangleq \boldsymbol{s} + \boldsymbol{n}'.\end{aligned} \tag{4}$$

It can be proven that $\boldsymbol{n}'$ gives raise to p parallel AWGN uncorrelated channels [7]. Thus, separation into parallel channels is accomplished in an ideal way, as unitary matrices increase neither transmitted power nor noise at receiver.

C. Application of SVD Decomposition to OFDM-CDM

In order to apply SVD decomposition to OFDM-CDM transmissions, it must be taken into consideration that multiple access interference is caused by spreading matrix $\boldsymbol{C}$

over signal vector. Because of this, channel equivalent matrix introduced in (1) is made up of spreading matrix $\boldsymbol{C}$ in conjunction with receiver estimated diagonal channel matrix $\boldsymbol{H}$, as

$$\boldsymbol{H}_{eq} = \boldsymbol{H}\boldsymbol{C}. \tag{5}$$

Taking (5) into consideration, it is clear that precoded signal vector to be transmitted, $\boldsymbol{x}'$, corresponds to

$$\boldsymbol{x}' = \boldsymbol{C}\boldsymbol{x} = \boldsymbol{C}\boldsymbol{V}\boldsymbol{s}. \tag{6}$$

IV. SIMULATIONS

Simulations carried out show both approximations taken to improve multi-carrier system performance, based on a 60 sub-carriers OFDM signal, transmitted at a rate of $1/30$ seconds per OFDM symbol. In every case sub-carriers are QPSK modulated. When plain OFDM transmissions are simulated, only 40 sub-carriers out of the 60 available ones are used, in order to keep the same overall rate for all transmissions. For this plain OFDM signal, Minimum Mean-Squared Error (MMSE) detector has been used at receiver.

When an application can tolerate some degree of delay, channel codification plus interleaving can by applied to OFDM signal, that is COFDM. For these simulations a $2/3$ convolutional coding has been used, with a code block length of 800 bits at coder input, turning thus into 1200 output bits. At reception MMSE plus Viterbi detector has been used.

For delay sensitive applications and CSI available at transmitter, OFDM-CDM and OFDM-CDM+SVD have been studied, both with and without BER-optimum power loading. In order to keep roughly the same data rate that in the case of COFDM, load of the OFDM-CDM system has been chosen at $2/3$, that is 40 symbols are spread over 60 available sub-carriers. For OFDM-CDM a MMSE receiver plus a MUD detector is used. For OFDM-CDM+SVD, where precoding is applied by joint processing of equivalent channel matrix SVD decomposition, at reception orthogonal matrix $\boldsymbol{U}$ introduced above is applied as a kind of MUD detector working as a decorrelator, thus presenting receiver with a diagonal equivalent channel matrix.

Simulations have been undertaken by use of a HF band ionospheric channel model. This doubly dispersive channel model has been validated by interactive digital voice modem real link measurements [8].

A. *HF Channel Model*

Long distance communications are feasible in the HF band thanks to ionosphere behavior as a passive reflector. However, atmosphere changing nature makes systems face a complex communication environment. Besides rapidly changing channel characteristics, multipath effects are always present. Typical values for frequency coherence in HF channel are about hundreds of Hz or less. Doppler spread usually varies between 0.1 and 2 Hz, while time spread is usually between 1 and 4 ms, thus making efficiencies over 0.5 bit/Hz difficult to achieve. It is common to find channel characteristics where several deep nulls are spread over the usually narrow transmission band and move arbitrarily over it. Because of all this, it is quit common to have available bandwidths smaller than 3 KHz for HF transmissions.

For the present simulations, a value of 0.5 Hz for doppler spread and 1 ms for time spread have been chosen. These values correspond to a moderate channel as defined by CCIR for HF simulations [9]. Noise bandwidth is 4,8 KHz.

B. *Results*

In the simulations presented below, OFDM, COFDM, OFDM-CDM and OFDM-CDM+SVD techniques have been considered.

Due mainly to the doubly dispersive nature of the HF channel OFDM-CDM with MUD detector performs similar to OFDM, both with MMSE receivers, in the range of Eb/No values considered, as shown in Figure 1. In order to increase performance in the HF channel, more elaborate techniques must be used.

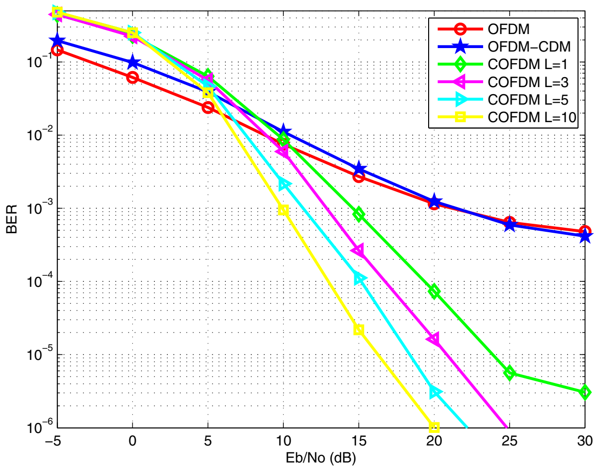

Figure 1: Performance comparison for non-CSI techniques

As a mean to cope with deep nulls and burst errors, channel coding and interleaving can be applied over plain OFDM, COFDM. In Figure 1 it can be seen how COFDM increases performance drastically, at the cost of communication delay, what makes it unsuitable for delay-sensitive applications. In that figure, interleaver depth, given as a multiple of code block length, has been labeled as L in the legend.

In order to asses interleaver influence in COFDM coding process, Figure 2 depicts BER values achieved, for some values of Eb/No, when COFDM is used with different interleaver depths, given as a factor of code block length. It can be seen that interleaver depth influences BER achieved only when some level of Eb/No is reached.

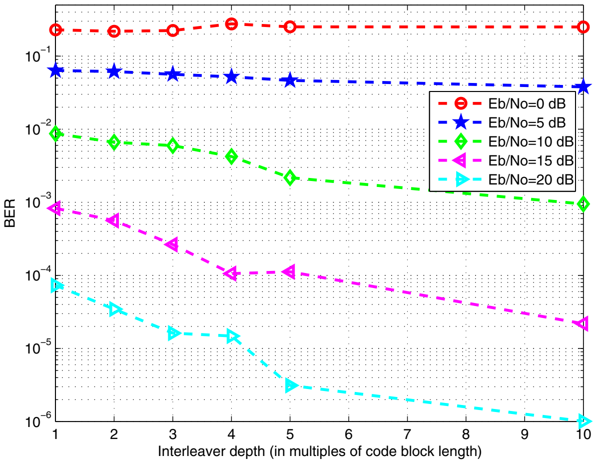

Figure 2: COFDM performance for interleaver depths

When CSI is available at transmitter, BER-optimum power loading of OFDM sub-carriers can be applied. In Figure 3 BER values achieved for OFDM with and without power loading are shown. As it was to be expected, neither plain OFDM nor OFDM with BER-optimum power loading at transmitter can cope with the doubly dispersive nature of the HF channel. Information carried by those sub-carriers affected by deep nulls gets definitely lost, thus causing a lower bound to the BER value that can be achieved. In order to overcome this limitation, besides power loading more complex CSI techniques must be applied, such as rate bit loading, where each sub-carrier is modulated at a different rate depending on the channel state at such sub-carrier. Rate bit loading has not been pursued as it is beyond the scope of this paper.

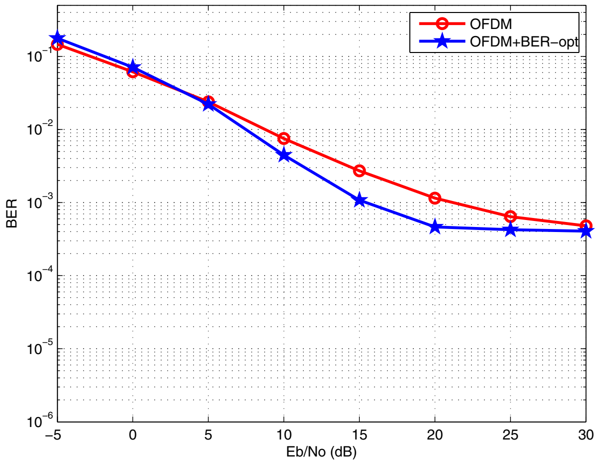

Figure 3: Performance comparison for OFDM

The last technique to be simulated is shown in Figure 4, where BER for OFDM-CDM is compared to that achieved when singular value decomposition is applied, OFDM-CDM+SVD. It is clearly shown how SVD decomposition outperforms plain OFDM-CDM, more and more as Eb/No increases, with no extra delay. This performance can be improved some more using BER-optimum power loading. These results show how on the one hand spread matrix helps cope with deep nulls, while on the other hand SVD decomposition can diagonalize equivalent channel matrix, given by spreading matrix and channel itself, minimizing MAI interference at receiver thanks to joint processing at transmitter and receiver.

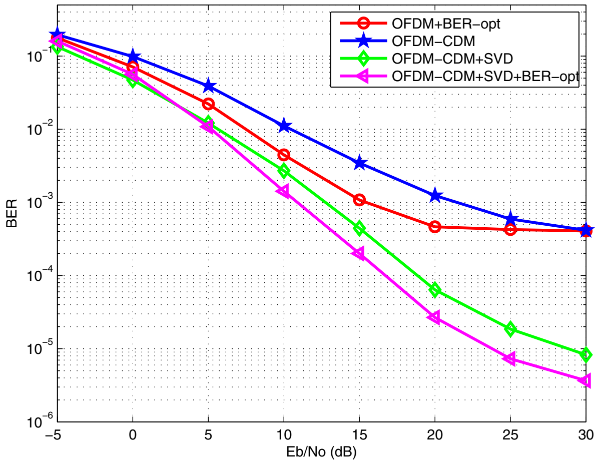

Figure 4: Performance comparison for CSI techniques

C. Conclusions

In this paper different techniques to improve multi-carrier systems performance on the HF channel have been studied, taking BER at receiver as a metric.

Multi-carrier modulation technique considered has been OFDM. On top of this one, two schemes have been applied allowing the system to cope with deep nulls and burst errors, namely channel coding and interleaving, COFDM, and orthogonal codes spreading, OFDM-CDM.

If the system can cope with communication delays, the classical technique to improve performance is COFDM, based on channel coding and interleaving. Simulations show that for a convolutional $2/3$ code and a MMSE receiver plus a Viterbi detector, performance is limited by Viterbi decoder need to have moderate Eb/No values. Once these values are reached, the deeper interleaver is, the higher performance gets. At low Eb/No values, either plain OFDM or OFDM-CDM perform better than COFDM, but as Eb/No gets higher, COFDM with any interleaver depth outperforms them both. Besides, up to moderate Eb/No values, as those used in this paper, OFDM-CDM and OFDM show nearly the same performance.

If CSI is available at transmitter, it is possible to increase system performance by processing without further delays. The simplest way to achieve this, is OFDM BER-optimum power loading. Although there is some performance gain, this is limited by the presence of deep nulls in the HF channel. Another simple technique to be applied to OFDM-CDM is equivalent channel matrix SVD decomposition, OFDM-CDM+SVD, that can also be reinforced with power loading. Considering perfect CSI, OFDM-CDM+SVD on its own increases performance drastically, with some extra increase when BER-optimum power loading is applied.

In this paper it is shown that application of CSI at transmitter, such as SVD decomposition, with or without added BER-optimum power loading, outperforms both OFDM and OFDM-CDM without further delays, thus making SVD decomposition a technique eligible for delay-sensitive applications on the HF channel if CSI is available at transmitter. Still, higher performance gains can be achieved with CSI if more complex techniques are to be used, such as bit rate loading.

V. ACKNOWLEDGMENTS

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