Multi-Antenna OFDM System Using Coded Wavelet and Weighted Beamforming

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Abstract. *A major drawback in deploying beamforming scheme in orthogonal frequency division multiplexing (OFDM) is to obtain the optimal weights that are associated with information beams. Two beam weighting methods, namely co-phasing and singular vector decomposition (SVD), are considered to maximize the signal beams for such beamforming scheme. Initially the system performance with and without interleaving is investigated using coded fast Fourier transform (FFT)-OFDM and wavelet-based OFDM. The two beamforming schemes are applied to the wavelet-based OFDM as confirmed to perform better than the FFT-OFDM. It is found that the beamweight by SVD improves the performance of the system by about 2 dB at the expense of the co-phasing method. The capacity performances of the weighting methods are also compared and discussed.*

Keywords

Beamforming, steering, MIMO, wavelet, OFDM, ISI, FFT, LTE, beam-weight.

1. Introduction

The wavelet transform (WT) has been introduced in the design of multicarrier communications systems in quite similar way to the well-known OFDM systems using the FFT [1-3], in which the FFT divides the selected wide-bandwidth into many narrow-bands and then provides many subcarriers for multiplexing input symbols. Meanwhile, WT contributes well suppressed side-lobes with low inter-symbol interference (ISI) and inter-carrier interference (ICI) index than there are in FFT-OFDM [1-4]. WT is also a windowed transform [5] with improved BER performance and can operate without a cyclic prefix (CP).

OFDM symbols can be coded, for instance using convolutional coding, against channel impairments with interleaving [6]. This provides the symbols with improved BER statistics at the expense of effective information rate since redundant bits are required. When decoded, the Viterbi algorithm [7] is used in the receiver with, either early signal quantization (hard-decision) or later quantization (soft-decision). While convolutional coding dominates multicarrier signaling in noisy channels, interleaving is remarked over impulsive distortions due to time variation of the channel response.

Hereafter consider the channel using co-phasing method [8], the degree of correlation of one multipath channel to another is increased thereby reducing the level of impulsive fading experienced by the transmitted symbols. This scheme is usually discussed as beamforming, for which the transmitted symbols may be weighted. It has been shown in [8] that, by harnessing the eigenvectors from the SVD of the channel as beam-weights, the system performance can be improved. It follows that, instead of co-phasing the transmit beams whose weights could represent the power with a number of transmitted antennas; each signal beam might be steered by some respective weight vector from the SVD to maximize the beam over some propagation media. Then, using WT-OFDM, one can observe this can do better than the FFT-OFDM when it is coded. Hence, different beamforming weights in a multi-antenna transmission are compared to establish the best operational performance.

The code structure used is described in Section 2 while the OFDM for different kernels are discussed in Sections 3 and 4. In Section 5, the beamforming scheme is described and simulation results are shown and discussed in Section 6 and then followed by summarized conclusions.

2. Convolutional Coding

The convolutional code structure discussed is similar to the INMARSAT standard-C earlier reported in [6]. It has ½ code rate and two polynomial generators G1 and G2 each defined by 1011011 and 1111001 (in binary form) respectively as in Fig. 1.

Like the name implied, there exist a convolution between the impulse response of the polynomial generator, **Gn**, n = 1,2, and the input bit. Hence, for d_i input bits occupying the prevailing memory register, then the output of the convolution of the i^{th} bit with k^{th} impulse response of the G_n^k polynomial generator (as shown in Fig. 1) becomes;

$$C_i = \sum_{i=0}^{L-1} d_i * G_n^k, \quad \forall \quad n = 1, \quad 2 \tag{1}$$

where '*' is the convolution operator, n represents the index of the polynomial generator and C_i represents the output coded bit. The resulted coded bits are mapped using QPSK or BPSK, for example, before OFDM modulation.

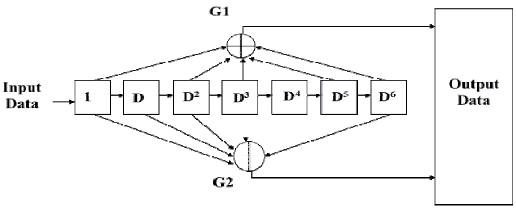

Fig. 1. Convolutional encoder.

3. Orthogonal Frequency Division Multiplexing

WT used in multicarrier signaling follows from the traditional OFDM systems which are designed using the FFT. Wavelets provide as many narrow-bands as the FFT. So, a WT-OFDM system divides a wide bandwidth into many smaller narrow-bands. If there are N-wavelet points, there will be N-narrow-bands. Meanwhile, an N-point FFT-OFDM system sampled at $t = nT$ can be represented as:

$$s[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} S_k e^{-j2\pi nk/N}, n = -N_g, \cdots, -1, 0, 1, \ldots, N-1 \tag{2}$$

where $\sqrt{N}$ is a scaling factor with N as number of the sub-channels, T is the signal period, N_g is length of the CP and n is the index of the prevailing subcarrier. S_k represents the complex PSK or QAM modulated input symbols. The sub-channels are spaced equally from another by $\Delta f = 1/T$ such that $N\Delta f = N/T$. So, the individual available narrow-band sub-channel is modulated by the input bits, say, using QPSK.

4. Wavelet-OFDM

In WT, the multicarrier process can be expressed to contain the basis function of the scaling function as [9]:

$$x[n] = \sum_k \sum_{m=0}^{M-1} X_{k,n} \varphi_{m,n}(t) \tag{3}$$

where $X_{k,n}$ represents the n^{th} symbol that modulates m^{th}-waveform of the k^{th}-constellation. $\varphi_{m,n}(t)$ is the complex orthogonal basis function like in the traditional OFDM:

$$\varphi_{m,n} = \begin{cases} 1 & n = m \\ 0 & elsewhere \end{cases} \tag{4}$$

where m and n are scales and shifts respectively.

5. Information Beamforming

The beamforming technique was applied to achieve improved diversity gain instead of capacity gain [10] and in addition simplify the system implementation than other MIMO techniques. The beamforming requires that the received signal must be highly correlated and as such the antenna separation must be as close as possible [11]. In outdoor environments, the beamforming technique achieves better performance than in an indoor environment because the beamforming technique depends on the angle of arrival (AoA) spread of the received signal [12]. Consequently, the spatial correlation between the received symbols is high since the angular spread of an outdoor environment is lower than the angular spread of the received symbols in an indoor environment due to the degree effects of multipath.

5.1 Maximizing the Signal Beams (Weight Computation)

The beams of the input signal are usually weighted in beamforming scheme subject to specified constraint as example the power level. In the receiver, a maximum ratio combining (MRC) is applied. With MRC, these weights (w) have been discussed early by [13]; for which if w maximizes λ such that the probability of error is minimum [14], then the SNR due to MRC becomes;

$$SNR_{MRC} = \frac{\left(\sum_{i=0}^{k-1} |h_i|^2 \right) \lambda}{\sigma_z^{\ 2}} = \frac{\sum_{i=0}^{k-1} \alpha_i \lambda}{\sigma_z^2}. \tag{5}$$

Consequently, if the average SNR of a SISO system is defined by $SNR_{SISO} = |h_1|^2\lambda/\sigma_z^2$, then the diversity order of a MIMO system with k antennas by beamforming scheme gives:

$$SNR_{MRC} = \left(k |h_1|^2 \lambda \right) / \sigma_z^{\ 2} = k.SNR_{SISO} \tag{6}$$

Since there are usually one-power amplifier per antenna, then each antenna is power constrained such that the weight must not be greater than a threshold, say λ_T , as

$$|w_i|^2 \le \lambda_T, \quad \forall i = 0, 1, \cdots, k-1. \tag{7}$$

In most cases, λ_T is set as unity [14] for short-term power constraint or different for each branch for long-term power constraint [10].

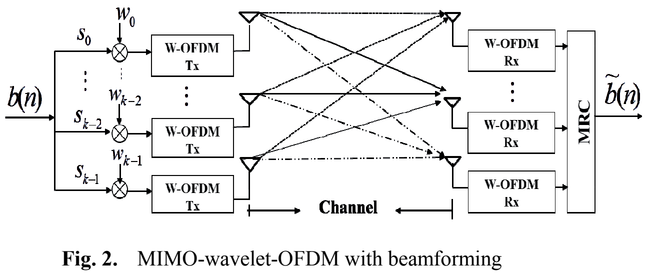

Fig. 2. MIMO-wavelet-OFDM with beamforming

Examples of these weights in MRC can be determined by eigen-filter approach and they could be the same irrespective of the signal branch correlation [15] or equivalently, the complex-valued (conjugate) channel gains [13], [16]. In this case, the optimal transmit beamforming weights can be obtained as;

$$w_i = \sqrt{\lambda_T / k} \cdot e^{-j\theta_i}, \quad \forall i = 0,1,\cdots,k-1 \tag{8}$$

λ_T can be set to 1 [13]. Equation 8 can be written as;

$$w_i = conj(\beta_i\, e^{-j\theta_i}), \quad \forall i = 0,1,\cdots,k-1 \tag{9}$$

where $\beta_i = \sqrt{\lambda_T / k}$ in (8). Fig. 2 is typical of an OFDM system with beamforming. The input symbols, at each antenna branch, are weighted by $W = [w_1 \quad w_2 \quad \cdots \quad w_k]^T$, $w_i \in C^{N_T \times N_T}$, $\forall i = 1,2,\cdots,N_T$ where $C^{N_T \times N_T}$ is a complex vector of $N_T \times N_T$ dimension, k is the maximum number of transmit antennas and $[.]^T$ is a transposition operation.

5.2 Weight Computation using SVD

The method for computing the weights for systems with beamforming whose channel state information (CSI) is known to the transmitter is shown in Fig. 3 [7].

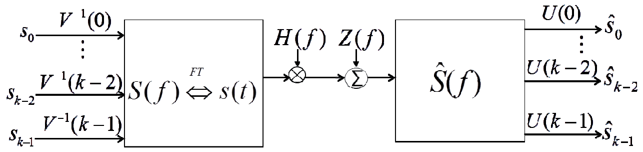

Fig. 3. Basic representation of beamforming weights and channel.

The beam-weights can be obtained from SVD property by letting the channel discussed from the SVD as [7];

$$H = U\,\zeta\,V\,. \tag{10}$$

U and V are eigenvectors of dimensions $N_T \times N_T$ and are $C^{N_T \times N_T}$. ζ is the diagonal containing eigenvalues. As shown in Fig. 3, the vectors that are characteristically given by $C^{N_T \times N_T}$, are used to weight the beam of each antenna branch.

5.3 Beamforming by Co-Phasing

Consider a multipath channel of the Rayleigh model with complex envelope as:

$$H = \sqrt{a^2 + b^2} \cdot e^{j\theta} \tag{11}$$

where a and b are *i.i.d* Gaussian variables from $h = a + jb$ and $\theta = \tan^{-1}(b/a)$. The signal beams can then be co-phased in the following way; if the transmit branches have signals with phases θ_i in $x_i = S \cdot e^{-j\theta_i}$, $\forall i = 1,2,\cdots,k$ where k is the maximum number of antenna elements, then the received symbols from different branches combine at the receiver can be given by:

$$X = \begin{bmatrix} h_1 & h_2 & h_3 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} + Z \tag{12}$$

where Z is the circular symmetry noise term with zero mean and unity variance. The weight factor in this case can be obtained from (10) as $\sqrt{\lambda_T / k}$. Thus, the beams are weighted respective to the number of transmitted elements. In this study, only 3 transmit branches are considered.

6. Simulation Results and Discussion

A typical multi-antenna scenario is presented for up to three transmit antennas. Input symbols are randomly generated and coded using the convolutional encoding structure described in Section 2 and then interleaved using a matrix interleaver. Its trace-back length is 32 to reduce computation time. There are 128 input symbols randomly generated and averaged 10^4 times, mapped using the BPSK and QPSK. In the first case, OFDM was constructed using the FFT and then the wavelet transforms. The DWT and WPT are also investigated. Over each transmission branch for CSI condition, the OFDM is performed and the signals convolved with the channel.

6.1 Coded Wavelet and OFDM Systems

The results for coded and uncoded OFDM systems constructed with three different kerneles, corresponding to single-input single-output system are shown in Fig. 4.

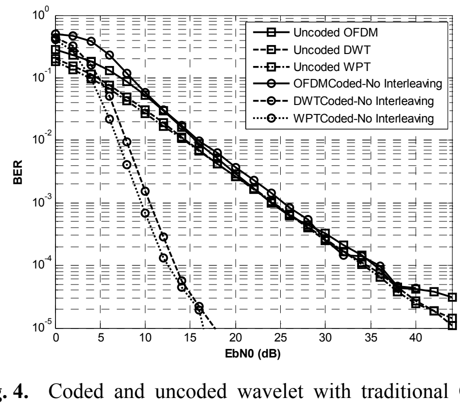

Fig. 4. Coded and uncoded wavelet with traditional OFDM compared.

In [6], it has been shown that the wavelet-based OFDM outperform the FFT-based OFDM. In WT the impulsive distortion effects of the multipath environment can be minimized.

The summarized results shown in Figs. 4 and 5, suggest the use of coded WPT rather than coded DWT or

COFDM in terms of BER performance as a proof of concept. Therefore, it is recommended to adopt the coded WPT for the SVD and Co-Phasing beamforming schemes.

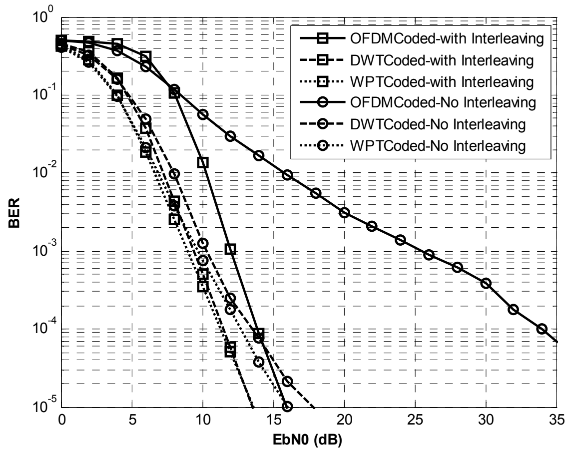

Fig. 5. Comparison of coded and uncoded wavelet with OFDM.

6.2 Beamforming with SVD and Co-Phasing for Uncoded Wavelet-OFDM

The co-phasing beam-steering technique is compared with the method for WPT multi-antenna system (3×1) using BPSK and QPSK in terms of BER and Capacity. Recall that the co-phasing is weighted as discussed in Section 5.3. *"BeamSteer"* is used for SVD and "*cof*" for traditional co-phasing in Figs. 6 and 7.

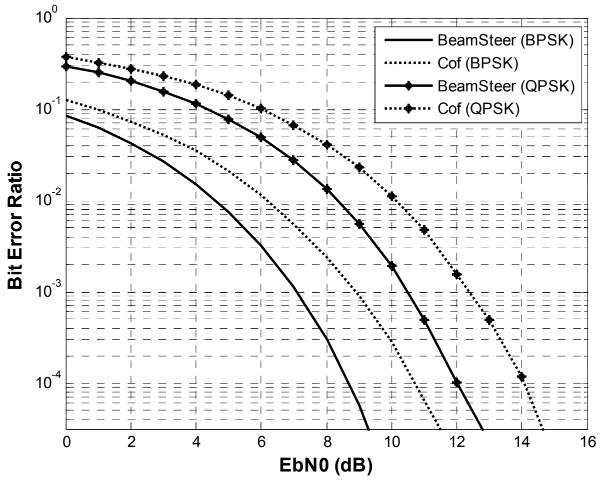

Fig. 6. Comparison of information weighted beam-steering and information beam co-phasing for uncoded WPT OFDM systems (3x1).

The co-phasing method improves the degree of correlation among the sub-channels in which the fading is reduced. However, the fading cannot be similar for all cases and using the steering weight improves the concentration of each received beam for every transmit branch. For BPSK and QPSK systems shown in Fig. 6, the SVD-based weights contribute about 2 dB gain for an uncoded WPT-OFDM system.

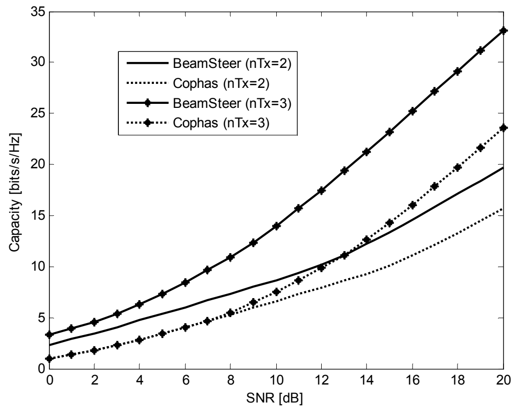

Fig. 7. Capacity performances for SVD weighted beamforming and co-phasing for uncoded WPT-OFDM systems (BPSK).

From the performance metrics of Figs. 6 and 7, the technology can be further extended for coded wavelet-OFDM for any mapping scheme. It can be conjectured based on the performances shown that coding will extend the performance of wavelet-beam weighted OFDM systems using SVD approach at the expense of the traditional co-phased. It is needless, therefore, to emphasize the case of the traditional OFDM. The side-effect in beamforming technology is the computation index since a full block of information is transmitted over different antenna spaces unlike in space-time block coding (STBC) wherein the information is coded in smaller number of bits (respective to the number of antenna spaces) for different time slots. Perhaps the propagation link severed the information beams (in beamforming), the likelihood of correctly decoding transmitted data will be reduced than in STBC.

7. Conclusion

A multi-antenna system based on beamforming with WT and FFT as the baseband kernels have been presented and discussed. It was found that WT-OFDM is sturdier over impulsive channel when coded than FFT-OFDM. Selected for further examination, WT-OFDM in multi-antenna design was shown for beamforming with two different weighting schemes. Although the co-phasing method has been used in discussing beamforming, the use of SVD beam-weights is now shown to outperform the traditional co-phasing beamforming method in terms of capacity and BER. Capacity plots confirmed the performance advantage of the SVD-weighted beamforming compared to the traditional co-phasing technique. It is conjectured that by combining the SVD weighted beamforming technique with coded WT-OFDM for multi-antenna design, it is possible that scheme can show greater improvement, than uncoded scheme.

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