Multi-Antenna OFDM System Using Coded Wavelet and Weighted Beamforming

Kelvin O. O. ANOH[1], Rameez ASIF[1], Raed A. Abd-ALHAMEED[1], Jonathan RODRIGUEZ[1,2], James M. NORAS[1], Steve M. R. JONES[1], Abubakar S. HUSSAINI[2]

[1] Mobile and Satellite Communications Research Centre, University of Bradford, Bradford, United Kingdom
[2] Instituto de Telecomunicacoes, Aveiro, Portugal

r.a.a.abd@bradford.ac.uk

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 beam-weight 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 ith bit with k^{th} impulse response of the G_n^k polynomial generator (as shown in Fig. 1) becomes;

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

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.
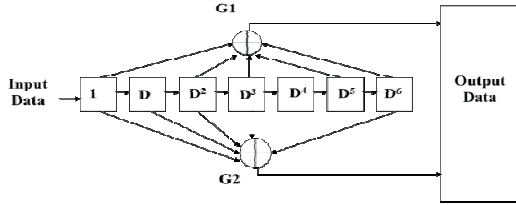

Fig. 1. Convolutional encoder.

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:

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

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 nth symbol that modulates m^{th}-waveform of the kth-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].
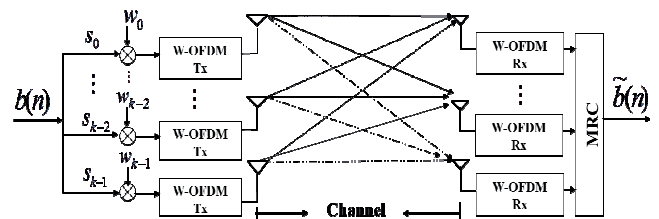

Fig. 2. MIMO-wavelet-OFDM with beamforming

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;

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

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

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

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].
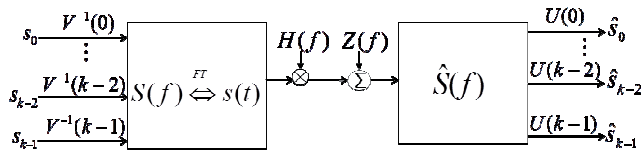

Fig. 3. Basic representation of beamforming weights and channel.

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

$$H = U \zeta V . \qquad (10)$$

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:

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

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:

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

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 kernels, corresponding to single-input single-output system are shown in Fig. 4.
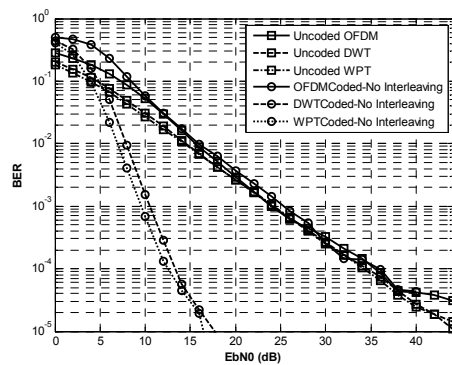

Fig. 4. Coded and uncoded wavelet with traditional OFDM compared.

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.
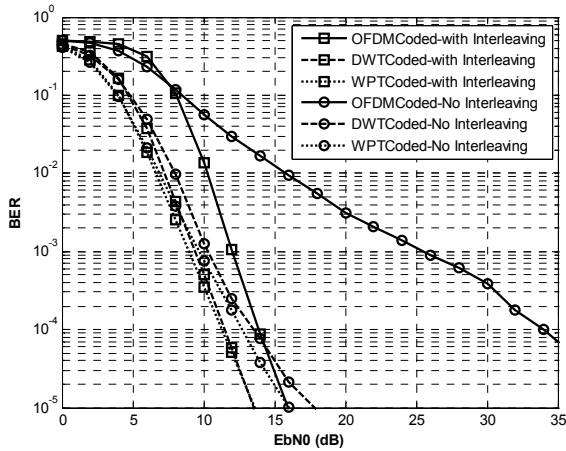

Fig. 5. Comparison of coded and uncoded wavelet with OFDM.

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.
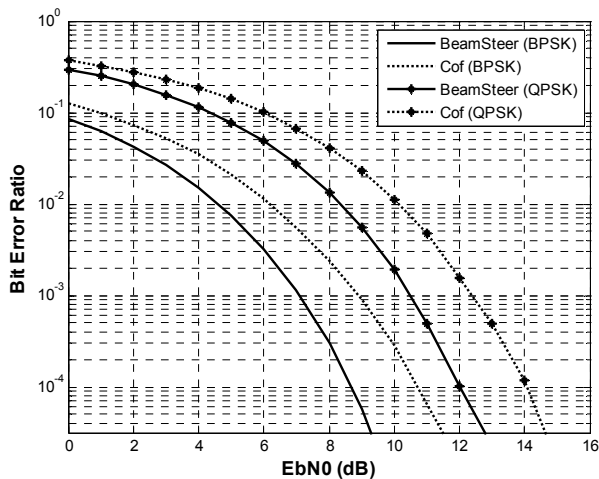

Fig. 6. Comparison of information weighted beam-steering and information beam co-phasing for uncoded WPT OFDM systems (3x1).

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.
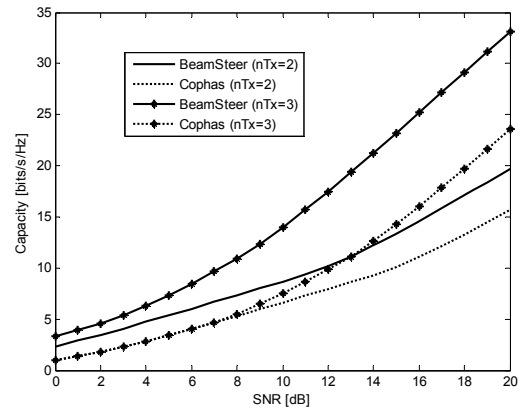

Fig. 7. Capacity performances for SVD weighted beamforming and co-phasing for uncoded WPT-OFDM systems (BPSK).

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.

Acknowledgements

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About Authors...

Kelvin O. O. ANOH is from Ohaozara, in Ebonyi State, Nigeria. He received his MSc degree in Data Telecommunications and Networks from the University of Salford-Manchester, UK, in 2010. Since 2011 to present, Kelvin pursues a PhD in Telecommunications Engineering at the School of Engineering, Design and Technology, University of Bradford, UK. He does well in mathematical modeling, system modeling, multicarrier communication systems - where he has published many papers – and cross-disciplinary research, and signal processing. He is a member of IEEE and (IET) since 2011.

Rameez ASIF was born in Lahore, Pakistan. He received the B.Eng. degree in Electronics and Computer Engineering from the University of Delaware, Newark, DE., U.S.A. in 2010 and M.Sc. (With Distinction) in Electrical and Computer Engineering from the University of Bradford, West Yorkshire, U.K., in 2012 and is currently a Ph.D. student at the University of Bradford, West Yorkshire, U.K. His main research interests are digital signal processing, ray tracing, wireless sensor networks and image processing. He has published several journal and conference papers. He became a student member for both IEEE and IET in 2011.

Raed A. Abd-ALHAMEED received the B.Sc. and M.Sc. degrees from Basrah University, Basrah, Iraq, in 1982 and 1985, respectively, and the Ph.D. degree from the University of Bradford, West Yorkshire, U.K., in 1997, all in Electrical Engineering. He is a Professor of electromagnetic and radio frequency engineering at the University of Bradford. He is the senior academic responsible for electromagnetics research in the Mobile and Satellite Communications Research Center, University of Bradford. Currently, he is the leader of the Communication Research Group and head of RF, antenna design and electromagnetics research in the School of Engineering, Design and Technology, Bradford University. He is Principal Investigator for the EPSRC-funded project "Multi-Band Balanced Antennas with Enhanced Stability and Performance for Mobile Handsets". He has also been a named co-investigator in several funded research projects. He is the leader for several successful knowledge transfer programmes such as Pace PLC, YW PLC, Datong PLC, WiMAC and ITEG Ltd. He is also a Research Visitor for Wrexham University, Wales, since September 2009, covering the wireless and communications research areas. He has pub

lished over 400 academic journal and conference papers and is coauthor of two books and several book chapters. He was awarded the certificate of excellence with grade "Outstanding" on 8th Feb. 2011, and the Business Innovation award on 13th April 2011, for the knowledge Transfer Partnerships with Pace Company for the period Jan. 2009 to March 2011, Certificate No. KTP007277, titled: Design, develop test a novel MIMO antenna system for wireless device communications. He is the Chair of several successful workshops on energy efficient and reconfigurable transceivers (EERT) approach towards energy conservation and reduction that addresses the biggest challenges for the future wireless systems. He was invited as keynote speaker for several international conferences such as, ICST, ITA and EPC; in addition to chairing many research sessions. He was appointed as Guest Editor for the *IET Science, Measurements and Technology Journal* in 2009. Prof. Abd-Alhameed is a Fellow of the Institution of Engineering and Technology, Fellow of Higher Education Academy, and a Chartered Engineer in the U.K.

Jonathan RODRIGUEZ received his Masters degree in Electronic and Electrical Engineering and Ph.D from the University of Surrey (UK), in 1998 and 2004 respectively. In 2002, he became a Research Fellow at the Centre for Communication Systems Research and was responsible for coordinating Surrey involvement in European research projects under framework 5 and 6. Since 2005, he is a Senior Researcher at the Instituto de Telecomunicações (Portugal), and founded the 4TELL Wireless Communication Research Group in 2008. He is currently the project coordinator for the Seventh Framework C2POWER project, and technical manager for COGEU. He is author of more than 170 scientific publications, served as general chair for several prestigious conferences and workshops, and has carried out consultancy for major manufacturers participating in DVB-T/H and HS-UPA standardization. His research interests include green communications, network coding, cognitive radio, cooperative networking, radio resource management, and cross-layer design. Dr Rodriguez has appointed as a research visitor to Bradford University since early 2013.

James M. NORAS is a Senior Lecturer in the School of Engineering, Design and Technology at the University of Bradford, UK. He has published 50 journal papers and 85 conference papers, in fundamental semiconductor physics, analog and digital circuit design, digital signal processing and RF system design and evaluation. He is the director of five internationally franchised BEng and MSc Courses in Electrical and Electronic Engineering, has successfully supervised 18 PhD students, and is currently supervising the research of 3 PhD students. His main research interests are now in digital system design and implementation, DSP and coding for communication systems, and localization algorithms for mobile systems. He is a Member of the Institute of Physics and a Chartered Physicist.

Steve M. R. JONES is a lecturer in Telecommunications and is a Director of Studies for programmes in Electronics and Telecommunications in the School of Engineering, Design and Technology at the University of Bradford. Since joining the University in 1987, he has worked on a wide variety of projects in the area of satellite slant-path propagation (e.g. 10 GHz bistatic-scatter, 11/14 GHz scintillation and ice depolarization with Olympus) and mobile radio propagation (notably Mobile VCE and TEAMS projects). He served as an Associate Editor for the IEEE Transactions on Antennas and Propagation 2004-8. Recently, he has worked on multiple-antenna technologies, signal processing and propagation modeling for broadband wireless access systems.

Abubakar S. HUSSAINI received his Diploma in Electrical/Electronic Engineering from the Bayero University (Nigeria) in 2003 with a specialization in Microwave/RF power amplifiers design and Tunable Filters; his MSc in Radio Frequency Communication Engineering and his PhD in Telecommunications Engineering from the University of Bradford in 2007 and 2012, respectively. He is a member of IEEE, IET, Optical Society of America; has contributed to numerous publications and is involved in European and CELTIC research projects. His research interests include radio frequency system design and high-performance RF-MEMS tunable filters with specific emphasis on energy efficiency and linearity and his achievements comprise the participation in the process to produce energy efficient power amplifier at 3.5 GHz (Mobile WiMAX frequency); the design and development of a "Radio over Fiber" optical transmitter and an optical receiver (1550 nm wavelength) in which the frequency limitations of quantum well lasers in direct RF to light transponding was investigated.