Improvements in Multicarrier Modulation Systems Using a Wavelet OFDM Scheme

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Abstract. This paper investigates the performance of wavelet OFDM signals over a wireless communications link. The scheme is shown to be generally similar to Fourier based OFDM, but with some additional features, and improved characteristics. The sensitivity of both schemes to the nonlinear amplification in the transmitter is compared by monitoring the time domain output data and the adjacent channel power ratio (ACPR) performance.

Keywords: wavelet transform, OFDM, ACPR.

1 Introduction

OFDM is often seen as an efficient means of delivering high speed wireless data links over a multipath fading environment, but suffers a major disadvantage in its peak-to-average power ratio (PAPR) [1]. High peaks in the OFDM transmit signals drive the power amplifiers (PA) operating near their nonlinear saturation region, reducing their power efficiency, and causing an overall degradation in the link performance. It is therefore necessary to transmit signals with a lower PAPR because of the operating range of the PA [1]. Existing research suggests a performance gain in wavelet based OFDM compared with Fourier based OFDM, owing to the superior spectral containment properties of wavelet filters. The characteristics of an OFDM modulated signal depend directly on the set of waveforms from which it has been constructed. Thus, any sensitivity to multipath channel distortion, synchronization error, and PA nonlinearities may be improved at this signal construction stage [2].

Wavelet based multi-carrier modulation, also known as wavelet (or filter bank) based OFDM has been studied in [3] and [4]. These wavelet OFDM systems possess all the broad advantages and disadvantages of Fourier based OFDM systems. However, in wavelet OFDM, the orthogonality is satisfied by orthogonal filter banks,

and no guard band interval (cyclic prefix) is needed, thus enhancing the bandwidth efficiency (20%) compared vs. Fourier OFDM systems. In addition, there is an additional bandwidth efficiency (8%) in wavelet OFDM, as pilot tones are no longer required [5] [6].

In this paper we focus on the sensitivity of Fourier and wavelet based OFDM to the nonlinear amplification in the transmitter by comparison with time domain data and ACPR performance. A resume of the wavelet packet transform is given in section 2, whilst in section 3 compares wavelet and Fourier OFDM for a representative system.

2   The Wavelet Packet Transform

The wavelet packet transform is a tool for analysing signals defined in the joint time-frequency domain, and is capable of providing simultaneous time and frequency domain data, as well as the combined time-frequency representation. The wavelets, or filter banks, under consideration possess better orthogonality compared with the more familiar orthogonal signal sets used [7]. In analytical terms they have compact support in both the time and frequency domain [8] [9]. Multi-resolution analysis allows wavelet and scaling functions to be represented by low pass (LP) and high pass (HP) conjugate mirror filters, respectively. These filter coefficients are denoted as $h[n]$ and $g[n]$, and satisfy the following conditions:

$$\left|\hat{h}(\omega)\right|^2 + \left|\hat{h}(\omega + \pi)\right|^2 = 2$$
$$|\hat{g}(\omega)|^2 + |\hat{g}(\omega + \pi)|^2 = 2$$
$$\hat{g}(\omega)\hat{h}^*(\omega) + \hat{g}(\omega + \pi)\hat{h}^*(\omega + \pi) = 0$$

The two orthogonal wavelet packet bases are defined as:

$$\Psi_{j+1}^{2p}(t) = \sum_{n=-\infty}^{\infty} h[n]\Psi_j^p(t - 2^j n)$$

$$\Psi_{j+1}^{2p+1}(t) = \sum_{n=-\infty}^{\infty} g[n]\Psi_j^p(t - 2^j n)$$

The wavelet basis set $\left\{\Psi_j^p(t - 2^j n)\right\}_{n\in\mathbb{Z}}$ is orthogonal, and represents the pth wavelet (packet function) at the jth level. This is an iterative decomposition, and the output coefficient vectors are reduced in size at each step by 2, eventually leading to a scalar output. This process is reversible, and the inverse discrete wavelet transform (IDWT) can be used to reconstruct the original input vector from the coefficient vectors. The action of the IDWT can be represented a series of up-sampling filters defined by $h[n]$ and $g[n]$. In Fig. 1 the decomposition and reconstruction trees are shown for 3-level wavelet packet, which may be used to illustrate demodulation and modulation, respectively.
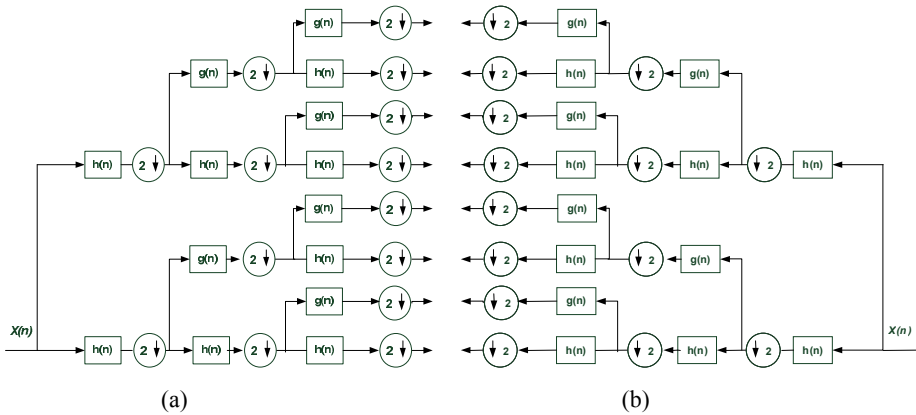
Fig. 1. Wavelet packet trees: (a) analysis/DWPT (b) synthesis/IDWPT

3   Wavelet Packet Based OFDM

The OFDM transmitter is implemented by the IFFT and the output OFDM frame is given by,

$$s_{OFDM}(m) = \sum_{k=0}^{N-1} a_k \exp\left(2\pi j \frac{k}{N} m\right)$$

where a_k denotes the data symbols, k is the sub-carrier index, and N is the number of subcarriers with inter-carrier spacing fixed as $\Delta f = T^{-1}$ (T being the symbol period). The OFDM system is illustrated in Fig. 2. One drawback of this scheme is the high PAPR associated with the OFDM signal, for which wavelet OFDM offers an alternative solution (Fig. 3). The modulated signal is initially converted from serial to parallel, as in the unmodified OFDM transceiver, but the IDWT is used in place of the IFFT. The transmitted signal takes the form,

$$s(m) = \sum_{p=0}^{N-1} \sum_{l=0}^{\infty} a_p(l)\Psi_{j,p}(m - lN)$$

where $a_p(l)$ are the modulated data symbols, and $\Psi_{j,p}$ is the reconstructed wavelet (packet) function. The action of the IDWT on a 64-QAM signal is given in Fig. 4. Our focus is on low frequency signals, so the modulated signals (a_p) perform a circular convolution with the LP filter, whereas the HP filter also performs the convolution with zeros padding the signal. The HP filter contains the wavelet coefficients. Different families of wavelet have different filter lengths, and hence approximated and detailed coefficients. Both filters must satisfy orthogonality to act as a wavelet transform. The up-converted analogue signal is sent to the power amplifier (PA), and the complex output of the memoryless PA envelope is given by,

$$w(s) = g(s) \exp\{j(\phi(s) + \theta)\}$$

where $s \mapsto s(t)$ is the amplitude of the complex input envelope, $\theta \mapsto \theta(t)$ is the arbitrary phase; the $g(\cdot)$ and $\phi(\cdot)$ are the AM-AM and AM-PM transfer functions, respectively [10]. The wavelet packet modulated (WPM) receiver signal is affected by the AWGN channel; in the receiver, the DWPT returns the signals to their original domain. Fig. 5 shows the signal at the input and output of the DWT, the estimation error is due the nonlinearity of the PA, and the AWGN.
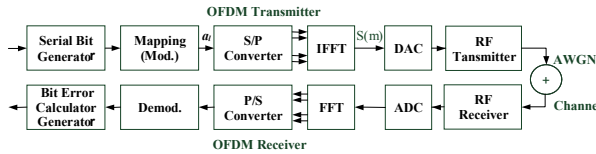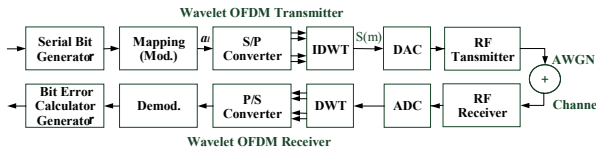
Fig. 2. OFDM Transceiver

Fig. 3. Wavelet OFDM Transceiver

The received signal is illustrated in Fig. 6, comparing with Fig. 5, it can be inferred that the wavelet based OFDM has optimal performance over the conventional OFDM, and that wavelet bases may offer a more logical choice for constructing orthogonal waveform sets. Referring to the power spectral density (PSD) of the wavelet vs. conventional OFDM, it can be seen that the wavelet OFDM has the greater spectral efficiency.
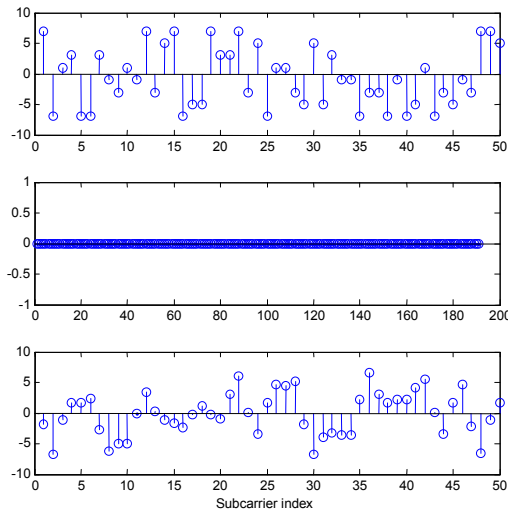
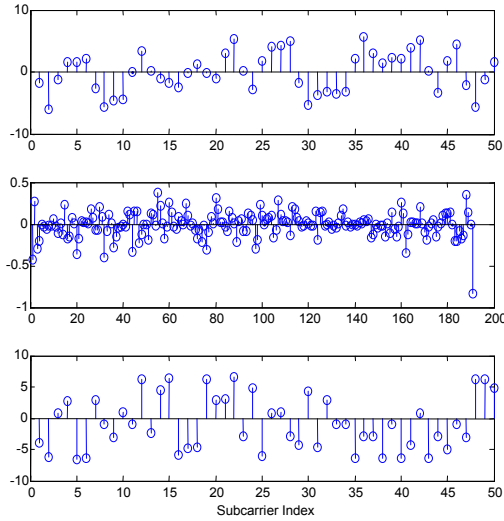**Fig. 4.** 64-QAM modulated signal (a) before IDWT (b) Coefficients of detail (c) signal after IDWT

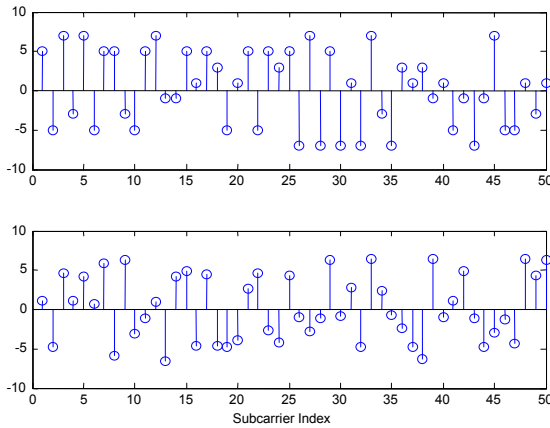**Fig. 5.** (a) Received signal before DWT (b) estimated Coefficients of detail (c) Received signal after IDWT

Fig. 6. Time domain OFDM signal

4   Conclusion

In general, the wavelet based OFDM provides an efficient performance owing to the superior spectral containment property of the wavelet filters. This paper suggests a new design approach for OFDM signals which display superior spectral efficiency, and the wavelet packet transform is employed to deliver a generalized OFDM modulation scheme.

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