Adaptive Performance Improvement of OFDM Radio over Fiber Systems

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Abstract—Nonlinear distortion due to large peak to average power ratio is a major concern with OFDM systems. In this paper, we present an efficient adaptive modulation technique to mitigate nonlinear distortion effects of OFDM radio signals transmitted over optical fiber (Radio-over-Fiber: ROF). First, we modulate all subcarriers at primary (high) level. Then we identify the subcarriers with high distortion and appropriately reduce the modulation level on those subcarriers to secondary levels. This is done at the transmitter side for each OFDM symbol. This procedure is repeated until the nonlinear distortion is below a predetermined threshold. This technique is shown to improve the BER performance considerably while the reduction in data rate for a system with 64 subcarriers and 16 QAM as primary and 4 QAM as secondary modulation levels is around 4%.

Index Terms—OFDM, Radio-over-fiber(ROF), nonlinear distortion, adaptive modulation.

I. INTRODUCTION

OFDM will be the most widely used technique for broadband communications for years to come. OFDM shows excellent performance in wireless (WiMAX, 4G) as well as in wired (DSL, broadband over power line) environments due to its robustness to frequency dependent impairments. In wireless environment, OFDM divides the frequency selective fading channel into number of flat fading channels and conquers. In wired environments like DSL, it provides robustness against reflections and high frequency attenuation.

There are many occasions in which OFDM modulated RF signals need to be transmitted over optical fiber, referred to as in OFDM-ROF systems [1]. An OFDM-ROF system may be followed by wireless channel (in fiber-wireless systems) or copper wire (in some DSL or fiber-coaxial systems) [2].

Although OFDM provides excellent benefits, the large peak to average power ratio (PAPR) is an important issue in OFDM systems that demands large linear range for the transmission channel. The radio-over-fiber links typically suffer from limited linear dynamic range due to the nonlinear distortion of the optical transmitter, either the laser diode or the Mach-Zehnder modulator (MZM).

The distortion caused by MZM/laser nonlinearity, increased average power requirement in intensity modulated optical systems, loss of orthogonality of subcarriers resulting in inter-carrier interference (ICI), increased hardware complexity and the need for more processing power are some issues of OFDM. The nonlinear distortion due to Laser/optical channel could be a major limiting factor in high speed wired/wireless OFDM systems employing thousands of subcarriers (eg:1024,2048,4096,8192). There has been a number of papers in recent times which concentrate on nonlinear distortion and peak to average power ratio (PAPR) reduction of OFDM systems [3], [4], [5], [6], [7].

In the paper [7] the authors illustrate that if information about the nonlinearity of the channel or the HPA/Laser is available at the transmitter side, then a better performance can be achieved by directly minimizing the distortion as a result of the nonlinearity rather than minimizing the OFDM signal’s PAPR. This approach is especially useful if the nonlinearity is relatively stable and can be estimated with sufficient accuracy as in the case of MZM/laser nonlinearity in radio-over-fiber systems. In this work we present a simple adaptive modulation technique for nonlinear noise mitigation in optical OFDM systems, assuming that information about the nonlinearity is available at the transmitter side.

II. SYSTEM MODEL

The baseband OFDM signal can be represented by,

\[ x(t) = \frac{1}{T} \sum_{k=0}^{N-1} X_k \exp(j2\pi k t/T), \quad 0 \leq t \leq T \]  

where, \( N \) is the total number of subcarriers, \( T \) is the OFDM symbol duration and \( X(k) \) is mapped \( M \) – QAM symbol as shown in Fig. 1. Since \( N \) is generally very large, according to the central limit theory, \( x(t) \) approximates Gaussian distribution, and its levels are infinite [7]. In high bit rate optical systems the Mach-Zehnder modulator is commonly used. It is shown in [6] that the baseband equivalent of this ROF section corresponds to a memoryless nonlinearity that can be characterized by a Bessel function of the first kind.

\[ f(\rho) = 2J_1(\frac{\pi \rho}{v_\pi}). \]  

where, \( \rho = |x(t)| \), and hence represents a pure AM-AM compression. \( v_\pi \) is a device parameter representing the smallest drive level for which the modulator produces \( \pi \) phase shift between its branches.

III. ADAPTIVE MODULATION TECHNIQUE

In this section we describe a simple algorithm to mitigate the nonlinear distortion assuming the nonlinearity can be estimated as described in [7]. For each OFDM symbol, its
corresponding time domain signal $x(t)$ is sent through the estimated nonlinearity and an FFT is performed at the received signal as shown in Fig. 1. Then the distortion on the symbols of each subcarrier is calculated. Then the subcarriers which experience high distortion are estimated and the modulation level on those subcarriers is reduced. Then the combined signal is again transmitted over the nonlinear device and the procedure is repeated.

When the distortion on all the subcarriers is below a certain threshold level, the OFDM symbol is transmitted over the actual ROF link along with side information containing the modulation info of each subcarrier. This approach differs from the criteria developed in [7] where the goal is to minimize the difference between the original OFDM time domain signal $x(t)$ and the estimated distorted time domain signal $x_{\text{distorted}}(t)$ after nonlinearity. However, in our approach we attempt to minimize the estimated distortion on each subcarrier (by taking an FFT after the estimated nonlinearity at the transmitter side as in Fig. 1).

This adaptive modulation approach is made possible since the serial bits to be transmitted are converted to parallel before OFDM modulation—that is we have the freedom to choose the modulation level of each subcarrier without having to change the modulation level of other subcarriers from the pool of available parallel bits. Another observation is that since the modulation levels on the subcarriers are independent, a change in one subcarrier would not considerably affect the time domain signal $x(t)$ according to the IFFT equation in (1) -this means the distortion effects after nonlinearity also would be relatively same except for the subcarrier position whose modulation is changed. Therefore by identifying the subcarriers (frequency positions) that are more likely to have distortion and reducing their modulation level we can improve the BER performance for the symbols on those subcarriers.

With our algorithm, $x(t)$ is passed through the estimated nonlinearity and an FFT is taken and the distortion on all subcarriers is estimated. The subcarrier indices whose distortion level exceeds a predetermined threshold ($d_{\text{thr}}$) are determined and sorted according to descending order of distortion. Out of these high distortion subcarrier indexes, only the first $\text{selection\_length}$ number of indexes are chosen as the selected subcarrier indexes and added to the solution set as described below. The modulation level of the entries in the solution set are reduced to a lower order. We need not reduce the modulation level on all the subcarriers whose distortion exceed the threshold. This is because when the modulation level of the highest distortion subcarriers are reduced it brings down the distortion level of other subcarriers as well. If the improvement on distortion of the other subcarriers still falls below the threshold, this procedure is repeated and more subcarriers are added to the solution set in the same manner.

When all the subcarriers have acceptable distortion levels ($<d_{\text{thr}}$) the algorithm exits and the subcarrier indexes collected in solution set are sent along with the OFDM symbol as side information (SI) with suitable error protection. It can be observed that this approach is essentially trading off bandwidth (or power) in order to improve the BER performance on the face of nonlinearity. However, by the suitable selection of $d_{\text{thr}}$ (according to the external noise processes) and fraction (according to the granularity desired) we can ensure that the desired BER performance is achieved with minimum compromise in bandwidth and complexity.

**Initial Setting**

initial modulation level for all subcarriers is set as, $\text{adaptive\_subcarrier\_info} = \{M_0, M_1, \ldots, M_{N-1}\}$, where, $M_k = \text{higher\_modulation\_order}$, $\forall_k$ a predetermined constant $d_{\text{thr}}$ is set as, $\text{threshold\_distortion\_level} = d_{\text{thr}}$, initially no subcarriers with distortion exceeding $d_{\text{thr}}$, $\text{subcarrier\_indexes\_with\_high\_distortion} = \{\}$, $\text{fraction\_of\_the\_distorted\_subcarriers\_to\_be\_considered} = \text{fraction}$, a predetermined constant

Initially no subcarrier indices selected to be added to the solution set $\text{selected\_subcarrier\_indexes} = \{\}$, $\text{solution\_set} = \{\}$, solution set for each iteration

![Fig. 1. Block schematic of the adaptive modulation system](image-url)
Fig. 2. BER vs. $E_b/N_0$ performance of OFDM without nonlinear distortion mitigation, with Symbol Interleaving, and Adaptive Modulation techniques.

Fig. 3. Received 16 QAM constellation without nonlinear noise mitigation.

Fig. 4. Received 16 QAM constellation with Symbol Interleaving.

Fig. 5. Received 16 QAM constellation with Adaptive Modulation.

Fig. 6. PSD after nonlinearity.

Step 1: Calculate the distortion of symbols in each of the subcarriers. The distortion vector can be given as,

$\text{distortion} = [d_0 \ d_2 \ \ldots \ d_{N-1}]$

If the distortion in all the subcarriers is below the threshold level,

$d_k < d_{\text{th},k}, \ for \ k \in \{0, 1, \ldots, N-1\}$

then exit the algorithm. Otherwise proceed to Step 2.

Step 2: Find the indexes of subcarriers which have distortion above the threshold level and sort them according to descending order of distortion.

$subcarrier\_indexes\_with\_high\_distortion = \{i_0, i_1, \ldots, \ldots\}$

where $d_{i_k} \geq d_{i_{k+1}}$ and $d_{i_k} \geq d_{\text{th}}, \ for \ k \in \{0, 1, \ldots, N-1\}$

Step 3: Divide the number of subcarriers in the sorted set by the predetermined length to find the number of subcarriers to be added to the solution set. Select the first $\text{selection\_length}$ subcarriers from $subcarrier\_indexes\_with\_high\_distortion$.
and make the selected_subcarrier_indexes list.

\[
\text{selection}_{\text{length}} = \left\lfloor \frac{\text{length(\text{subcarrier_indexes_with_high_distortion})}}{\text{fraction}} \right\rfloor
\]

\[
\text{selected_subcarrier_indexes} = \{i_0, i_1, \ldots, i_{\text{selection}_{\text{length}} - 1}\}
\]

**Step 4:** Update the solution set with selected_subcarrier_indexes. Determine the adaptive subcarrier info for the next iteration based on the entries in the solution set. Go to Step 1.

\[
\text{solution_set} = \text{solution_set} \cup \text{selected_subcarrier_indexes}
\]

\[
\text{adaptive_subcarrier_info} = \{M_0, M_1, \ldots, M_{N-1}\},
\]

where \(M_k = \text{higher_modulation_order} \text{ if } k \notin \text{solution_set}\), \(M_k = \text{lower_modulation_order} \text{ if } k \in \text{solution_set}\).

**IV. Performance Evaluation**

For the simulation of the proposed adaptive modulation technique to mitigate the nonlinear distortion the following parameters are chosen. An OFDM system with \(N = 64\) subcarriers with 16 QAM as primary (higher rate) modulation and 4 QAM as secondary (lower rate) modulation (when the nonlinear distortion is above the threshold) is chosen. No restrictions are placed on the number of iterations on the adaptive algorithm. The performance is compared with the Symbol Interleaving technique presented in [3] with the number of interleavers taken to be 20. A memoryless nonlinearity characterized by a Bessel function of the first kind as described in section II is used to model the nonlinear system with the value \(\pi/V_e\) taken to be 1. To perform adaptive modulation it is assumed that information about the nonlinearity is available (estimated with sufficient accuracy) at the transmitter.

Fig. 2 compares the BER performance of the adaptive modulation technique with the symbol interleaving technique. It is evident that the proposed technique brings significant improvement to the BER curves.

However, the analysis is not complete without a comparison between the data rate reduction of the proposed technique and its complexity. The average transmission efficiency (transmission efficiency = \(\frac{\text{number of bits transmitted}}{\text{number of bits that could be transmitted}}\)) of this technique is found to be around 90.77%, whereas, the transmission efficiency of the symbol interleaving technique is 100% as it involves no reduction in the data rate. The adaptive modulation algorithm takes on average 24305 iterations to converge per OFDM symbol. Each iteration requires 2 FFT operations (1 IFFT and 1 FFT) and also it consists of the demodulation and distortion estimation parts. However, the complexity could be further reduced if one considers the symmetrical nature of the IFFT matrix and the fact that only the modulation of a fraction of the subcarriers is reduced in each iteration. The complexity of the symbol interleaving solution (in the considered case of 20 interleavers) is 20 FFT operations per OFDM symbol and in this case the complexity cannot be further reduced by considering the symmetrical nature of the FFT operation as each interleaver permutes the data symbols in a pseudo-random order. However, this technique does not estimate the distortion noise and hence it has a lesser complexity on that aspect.

Fig. 3, Fig. 4 and Fig. 5 illustrate the received symbol scatter diagrams. The scatter diagrams are obtained without considering the effect of AWGN.

**V. Conclusions and Future Research**

In the adaptive modulation scheme to mitigate the nonlinear distortion, a calculation is done at the transmitter side which identifies the subcarriers with high distortion and correspondingly reduces the modulation level on those subcarriers. This procedure is repeated recursively until the nonlinear distortion is below a predetermined threshold. This method outperforms OFDM without distortion mitigation. For example the improvement is 6 dB compared to OFDM without distortion mitigation and 2 dB compared to the symbol interleaving technique [3] at a BER of \(10^{-2}\). Furthermore, these two previous techniques show an irreducible BER due to nonlinear distortion even at high signal to noise ratios. Our technique has progressively diminishing BER at high SNR. The data rate reduction in this method is 4%.

We estimated the distortion after nonlinearity only by running the simulation. It would be a useful contribution to estimate the distortion analytically. For example, for a polynomial nonlinearity the distortion of a given signal can be estimated in frequency domain using a convolution according to the polynomial coefficients.

**References**


