PERFORMANCE OF CLIPPED OFDM SIGNAL IN FIBER

Debashis Chanda, Abu Sesay and Bob Davies
Electrical and Computer Engineering Department, University of Calgary, Calgary, Canada
{chandad, sesay}@enel.ucalgary.ca, davies@cal.trlabs.ca

Abstract

Combined deployment of optical fiber technology and wireless networks has great potential for increasing the capacity and Quality of Service. By using Radio-over-Fiber (ROF) technology, the capacity of optical networks can be combined with the flexibility and mobility of wireless access networks without significant cost increment. The Radio-over-Fiber concept means to transport information over optical fiber by modulating the light with the radio signal. This article discusses the effects of using fiber in conjunction with wireless local area network standard 802.11a (WLAN) to distribute RF signal. To achieve high throughput 802.11a LAN uses Orthogonal Frequency Division Multiplexing (OFDM) based multi-carrier wideband modulation technique. OFDM is one of the most favored modulation techniques in WLAN scenario due to its efficient implementation and robustness against multi-path and narrowband interference. One of the biggest drawbacks of OFDM is its high peak to average power ratio (PAPR). High PAPR of OFDM makes it unusable in non-linear systems. In this article we will discuss better ways to overcome PAPR problem of OFDM signal which will improve its performance in fiber.

Keywords: *Mach-Zehnder Electro-Optic Modulator, Orthogonal Frequency Division Multiplexing, Peak to Average Power Ratio, Wireless on Fiber.*

1. INTRODUCTION

Wireless LAN carried by optical fiber is an attractive option for high data rate, short-range links, where deploying optical fibers all the way to the customer premises is too expensive or otherwise impractical. The primary objective of this article is to investigate the technical difficulties of using an integrated optical and wireless infrastructure capable of delivering broadband multimedia traffic to subscribers in remote areas. In such a scheme, the fiber is used to route the broadband modulated optical signals to base stations where the RF signals are detected and transmitted to client stations. The use of RF over fiber allows a significant reduction in the complexity and costs of remote base stations. It also provides an inexpensive method for system upgrades, since most of the signal processing functions would be done at the central office and not at each individual base station.

The use of fiber optics to transport digital signals is quite common. However, the transmission of analog RF signals has been limited by the linearity constraints in modulating/demodulating devices, and by the distortion effects created by the optical link. To transport WLAN through fiber, OFDM based radio signal is superimposed on optical carrier by intensity modulation of optical carrier using Mach-Zehnder (MZ) electro-optic modulator. MZ modulator has a sinusoidal electrical to optical power transfer characteristics which restricts OFDM signal to occupy a narrow dynamic range in the most linear region of the power transfer curve. Due to high PAPR, OFDM signal has low average power and causes non-linear distortion when transported through fiber. To overcome this limitation over-sampled OFDM envelope has been clipped at baseband, which reduces PAPR of OFDM signal. Due to dense sub-carrier spacing of OFDM signal, baseband clipping causes frequency leakage across the sub-carriers. To reduce spectral spreading, clipped peaks are windowed in an efficient manner. It can be observed that clipped-windowed OFDM signal is much more robust against MZ nonlinear distortion.

2. WLAN ON FIBER SYSTEM

2.1 802.11a LAN

802.11a LAN uses Orthogonal Frequency Division Multiplexing (OFDM) as modulation technique. OFDM has several properties, which make it an attractive modulation scheme for high speed transmission link like 802.11a LAN which supports up to 54Mbps of data rate. In OFDM based system powerful channel equalization is not needed to combat ISI and if differential modulation is applied, no channel estimation is required at all. Thus, the complexity of OFDM systems can be

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much lower compared to a single carrier transmission system. 802.11a LAN appends guard interval in each symbol to reduce multi-path effects. It also uses a special preamble in each frame for frame synchronization, channel estimation and frequency offset estimation at the receiver end. Complex baseband OFDM signal is up converted to RF domain. Upconverted signal is used to intensity modulate a CW Laser using Mach-Zahnder Modulator. For detailed implementation of 802.11a LAN see [1]-[2].

2.2 OFDM Signal Representation

The OFDM baseband signal for N subcarriers is formed as:

$$x(t) = \sum_{n=1}^{N} (a_n \cos \omega_n t + j b_n \sin \omega_n t) \qquad (1)$$

where a_n and b_n are the in-phase and quadrature modulating symbols. At first raw data is mapped according to BPSK / QPSK / 16-QAM / 64-QAM depending upon data rate. Each complex data ($a_n + j\, b_n$) is amplitude modulated on orthogonal subcarriers. This process is performed using Inverse Fourier Transform (IFFT) which guarantees that all the subcarriers are orthogonal to each other over the symbol interval [2].

3. OFDM SIGNAL IN FIBER

3.1 PAPR Problem of OFDM Signal

One major difficulty with OFDM is its large peak-to-average ratio (PAPR) which distorts the signal if the transmitter contains nonlinear components. The PAPR is defined as [2]:

$$PAPR = \frac{\max_{0 \le t \le T} |S(t)|^2}{P_{av}} \qquad (2)$$

The nonlinear effects on the transmitted OFDM symbols due to high PAPR are spectral spreading, intermodulation and harmonic generation [3]-[4]. In other words, the nonlinear distortion causes both in-band and out-of-band interference to signals. The in-band interference increases the BER of the received signal through warping of the signal constellation while the out-of-band interference causes adjacent channel interference through spectral spreading. The latter is what prevents the usage of OFDM in many systems even if the in-band interference is tolerable. Therefore the nonlinear device requires a back-off which is approximately equal to the PAPR for distortionless transmission. Therefore reducing PAPR has high practical interest.

In Wireless LAN on Fiber scenario high PAPR of OFDM signal is not desirable because Mach-Zehander electro-optic modulator has highly nonlinear power transfer characteristics. So before sending the signal over fiber PAPR of the signal has to be reduced.

3.2 PAPR Distribution in OFDM Signal

From central limit theorem for large value of N real and imaginary components of x(t) in equation (1) become Gaussian distributed with zero mean. So the complex envelope of x(t) has Rayleigh distribution and consequently the power of complex envelope of x(t) possesses Chi-Square distribution with two degrees of freedom [3]. As quadrature random processes are zero mean Gaussian process, the power distribution will be central Chi-Square distribution given by:

$$F(z) = p(u \le z) = \int_0^z \frac{1}{2\sigma^2} e^{\frac{-u}{2\sigma^2}} du$$
$$F(z) = p(R \le z) = \int_0^z \frac{1}{2} e^{\frac{-R}{2}} dR \qquad (3)$$

Where u is the complex envelope power of x(t). So $R = u/\sigma^2$ represents envelope power to average symbol power ratio. Now we want to derive the cumulative distribution function of peak envelope power to average symbol power ratio (PAPR) per OFDM symbol. If we assume that all the samples are uncorrelated then this can be written as:

$$C(z) = p(\max(R) \le z) = F(z)^N$$
$$C(z) = [1 - \exp(-\frac{z}{2})]^N \qquad (4)$$

The assumption of uncorrelated samples will not hold good for baseband oversampled OFDM signals. In that case if oversampling ratio is Γ then among $\Gamma.N$ samples we can assume that $\beta.N$ are uncorrelated where β is greater than one. So C(z) becomes:

$$C(z) = [1 - \exp(-\frac{z}{2})]^{\beta.N} \qquad (5)$$

In Fig. 1 dotted lines are simulation results and solid lines are theoretically calculated curves. Here number of subcarriers per OFDM symbol is 64 and oversampling ratio is 6. It can be seen that for low PAPR theoretical and simulated results closely match one another. Also, it can be noticed from the plots that the probability of high PAPR is very low, which will in turn vindicates the use of clipping to reduce high peak to average power ratio of OFDM signal before sending the signal over fiber.

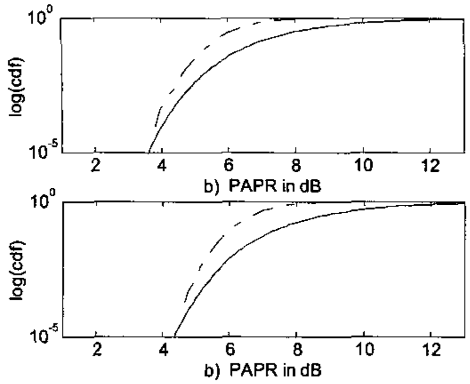

Fig. 1. a) cdf of non-oversampled signal b) cdf of oversampled signal

3.3 PAPR Reduction in Fiber

Coding is a desirable method to reduce the PAPR for small number of carriers since it does not introduce any distortion to the signal. As the number of carriers increases, however, coding becomes intractable since the memory needed to store the codebook and the CPU time needed to find the corresponding codeword grows exponentially with the number of carriers. As discussed in section 3.2 the occurrence of high PAPR is very low so baseband envelope clipping of OFDM signal is very effective method in reducing PAPR, whose efficiency does not depend on the number of carriers [4]. However clipping process generates in band as well as out of band clipping noise.

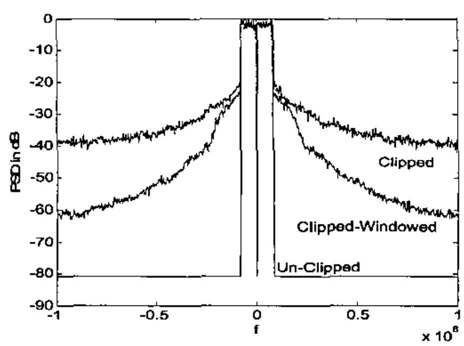

Fig. 2. Baseband OFDM Spectrum

As shown in Fig. 2 clipping causes significant spectral leakage into adjacent channels. Here the clipped peaks are windowed to reduce spectral leakage due to clipping. But the effects of clipping or clipped peak windowing in generating in band noise are not evident here. We have to evaluate it through constellation error or other methods which will be elaborated in next sections.

4. NONLINEAR EFFECTS OF OPTICAL SYSTEM ON OFDM BASED WLAN

4.1 MZM Power Transfer Characteristics

Mach-Zehnder modulator is one of the main sources of nonlinear effects in optical systems [5]. In this article we will only concentrate on MZM nonlinear effects. Mach-Zehnder modulator has highly nonlinear Electrical to Optical power transfer characteristics which restricts OFDM signal to occupy a narrow dynamic range in the most linear region of the power transfer curve.

$$P_o = P_{in}.k.[1 + \cos(\pi \frac{v_{RF} - v_{Bias}}{v_\pi})] \qquad (6)$$

Here Po is the optical power output and Pin optical power input. Due to cosine term in the power transfer characteristics, OFDM signal with high PAPR is not suitable for wireless LAN over Fiber scenario using MZM. To overcome this limitation baseband OFDM signal is clipped and clipped peaks are windowed before putting the up-converted OFDM signal on optical carrier using MZM. To suppress even harmonics, MZM is biased at quadrature bias points $V_Q = \pm k.V_\Pi/2$ where k is odd.

4.2 MZM Nonlinear Effects

Due to nonlinear power transfer characteristics MZ modulator generates harmonics and intermodulation products if modulation index of input RF signal exceeds a certain limits. In the Fig. 3 we can see that with the increase in the gain of RF input of MZ modulator, Modulation Index (MI) of MZM increases. Modulation Index of MZM is defined as:

$$MI = \pi \frac{\max(v_{RF})}{V_\pi} \qquad (7)$$

The increase in MI is much lower in case of baseband clipped and windowed signals with respect to un-clipped signal. So these signals have lower dynamic range and low PAPR which can be seen in Fig. 3. Here SSBB-Clipped stands for single sided baseband clipped signal and DSBB-Clipped stands for double sided baseband clipped signal. Single sided baseband clipping has been performed 3dB above RMS signal power and double sided baseband clipping has been performed 6dB below RMS signal power and clipped peaks are windowed with different windows which will not be elaborated here for brevity of the article. It can be observed that clipped-windowed signal has lower dynamic range and lower peak to average power ratio.

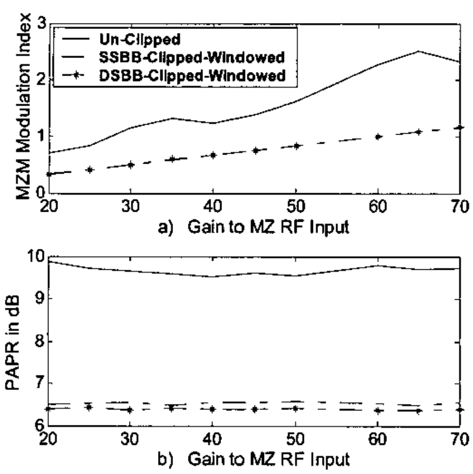

Fig. 3. Dynamic Range of Signals

From Fig. 4b we can see that with the increase in MI out of band power due to MZ nonlinearity increases. We have considered here out of band power across third harmonic RF carrier. We can notice that clipped-windowed signal has lower out of band power compared to unclipped signal which is highly desirable in multi channel operations. For single channel operations there are no intermodulation products due to nonlinearity. But for OFDM signal there will be intermodulation products because OFDM signal is comprised of closely packed sub-carriers across DC in case of baseband and across RF carrier in case of passband. That is why OFDM signal will generate intermodulation products among closely packed sub-carriers due to nonlinearity in case of single channel operation as well. Out of band intermodulation products and harmonics will not affect performances because they will be filtered out for single channel operation. But in band intermodulation products can not be removed and will deteriorate system performance. The clipped OFDM signal at MZM output can be written as:

$$S(t) = X(t) + N_{Clip} + N_{Additive} + N_{NLD} \qquad (8)$$

Where X(t) is the original signal component, N_{Clip} is in band clipping noise, $N_{Additive}$ is in band additive white gaussian noise, N_{NLD} is noise due to MZ nonlinear distortion in the form of in band intermodulation products. From Fig.4 we can see that RMS constellation error of Clipped-Windowed signal is independent of MZ modulation index. Here RMS constellation error has been plotted against gain of MZM RF input instead of MZ modulation index. Because Un-clipped and clipped signals possesses different modulation index after clipping process (eq.6). Fig. 3a shows modulation index verses gain of MZ RF input graph for different signals. After clipping process clipping noise (N_{Clip}) remains constant and it is independent of MZ modulation index.

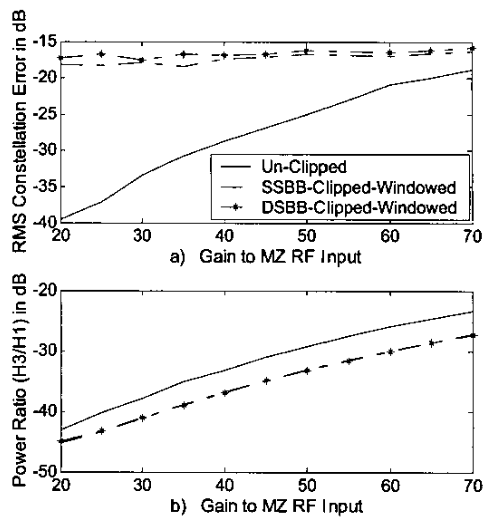

Fig. 4. a) Constellation Error b) Out of Band Power

However the noise generated due to MZ nonlinearity (N_{NLD}) is dependent on MI of MZM. Here N_{NLD} is caused due to intermodulation of OFDM subcarriers. We can observe from Fig. 4a that clipped-windowed OFDM signal is more robust against N_{NLD}. It does not depend on modulation index of MZM.

5. CONCLUSIONS

Designing a proper clipped peak smoothing window is very critical, which we have not elaborated in this article. In absolute scale, unclipped signal perform better than clipped signal which we can observe from Fig. 4a. This happens due to the fact that clipping process eliminates portion of information bearing signal during clipping operation which is an irreversible process. However if we consider low Peak to Average Power Ratio, low out of band noise generation and robustness against MZ nonlinearity then clipped-windowed signal is more suitable than unclipped signal in optical systems.

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