On the Nonlinear Distortion Effects in an OFDM-RoF Link

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Abstract: *Radio over Fiber (RoF) system is a promising technique for microcell and picocell applications for deployment of future ubiquitous wireless data networks. However, the performance of RoF systems can be severely degraded due to non-linear effects in the channel. Also, Orthogonal Frequency Division Multiplexing (OFDM), as a standard for broadband wireless networks, is being proposed for deployment with RoF systems to facilitate the total performance of a system. In this research, at first, the performance of OFDM-based RoF link with Mach-Zehnder modulator distortion effects has been analyzed at 5.8 GHz. Evaluation of mean-squared error of the proposed OFDM-RoF system was carried out to compare with the conventional single carrier system based RoF link after the modulator distortion case and also for fixed Signal to Noise Ratio (SNR) of 20 dB using undistorted OFDM signal. Later, nominal and offset biasing pre-distortion techniques are applied in proposed system to linearize the OFDM-RoF link. Thus, finally a comparison between the aforementioned pre-distortion techniques applied showed important observation in terms of distortion-free dynamic range and SNR to choose offset pre-distortion technique for our proposed system.*

1. INTRODUCTION

Due to high Peak to Average Power Ratios (PAPR), nonlinear distortion effects have become an important parameter to consider for OFDM [7]. However, OFDM proved its robustness against time-dispersive impairments such as multi-path fading and impulsive interference combined with a spectral efficiency that rivals single carrier systems. So, these factors have eventually led OFDM to be a universally-adopted modulation schemes for broadband wireless deployments.

For broadband fixed-point wireless access systems, RoF is a proposed solution for alternative network architecture [7]. RF technology is appropriate to interconnect control stations(CS) and base stations(BS) in these recently proposed wireless networks, thereby allowing the concentration of complex equipments in the CS and the simplification of CS [1]. Optical modulators used are the primary sources of nonlinear distortion in RoF links. Mach-Zehnder modulator used in many analog optical links causes a highly deterministic non-linearity. Since OFDM is subjected to high PAPR, it is of particular interest to observe the effects and suitability of OFDM in an OFDM-RoF linked system.

Previous research demonstrated the congeniality of RoF for the transmission of single-carrier and spread spectrum signals, see [4, 5]. Therefore, similar experimentation is required for OFDM whether it performs similarly in a RoF link using Mach-Zehnder modulator under nonlinear distortion effects than that of single carrier systems, particularly in IEEE 802.11a wireless LAN standard.

Also, the distortion effects can be mitigated using suitable pre-distortion techniques in an OFDM based RoF link and thus the system performance can be improved in terms of increased distortion-free dynamic range and SNR. Previous research only concentrated on the OFDM system to evaluate performance by applying PAPR reduction techniques or pre-distortion techniques as in [8, 9] and did not consider an OFDM based RoF link to assess similar performance.

In this paper, the performance characterization is simulated for an OFDM-RoF system at 5.8 GHz to observe the non-linear distortion tolerance of OFDM signal on a link using Mach-Zehnder modulator in terms of

mean-squared error (ME). After that, the results are compared with the single carrier based RoF link systems. Then, nominal and offset biasing pre-distortion techniques are applied on OFDM-RoF links and compared with the original system without applying pre-distortion techniques to finally decide an efficient optical interconnected wireless system.
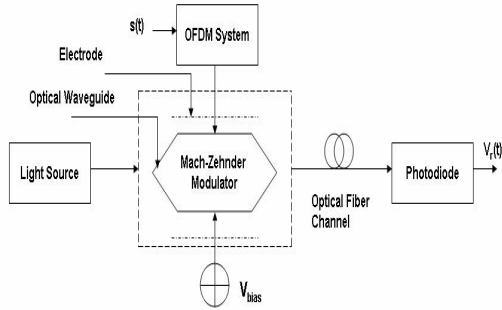

Figure 1. System Model

2. SYSTEM MODELING

Consider a single OFDM symbol

$$s(t) = \sum_{n=-N/2}^{N/2-1} d_n \cos((\omega_c - n\Delta\omega)t + \theta_n) \quad (1)$$

where N is the number of subcarriers separated from each other by $\Delta\omega$ and centered at ω_c. d_n and θ_n are respectively the magnitude and phase of n subcarriers.

The OFDM signal $s(t)$ is transmitted over an optical link. The electrical signal i.e. OFDM signal is used to modulate the intensity of light to be used in the fiber channel. This electro-optic (E/O) conversion can be accomplished in two ways: by directly modulating the intensity of the light source or by using a constant-intensity source followed by an external modulator.

Because OFDM has large peaks due to its high PAPR and is normally used at RF center frequencies above 5 GHz, external modulation e.g. Mach-Zehnder modulator is preferred for the transmission of the standard OFDM signals of interest. A block diagram of the proposed system is shown in Figure 1 above.

The detected power after the signal has travelled through a length L_f of fiber is [2]

$$P_0(L_f)_{dB} \; \alpha \; 10\log\left\{\cos^2(\frac{\pi DL_f\lambda_0^2 f_c^2}{c})\right\} \quad (2)$$

where D is a dispersion parameter usually expressed in units of ps/(nm-km), λ_0 is the wavelength of the optical source, and c is the speed of light in free space.

For the OFDM based RoF link in our model, the loss due to fiber attenuation would be no more than 3 dB assuming the base stations in the central offices will not be located more than 5 to 6 km from the remote stations. Therefore, it is insignificant in comparison to the large losses expected in the wireless components of the channel and is not considered in our model therefore.

In this paper, only power gain G_{fiber} was assumed for the fiber without considering other distortions of the fiber and therefore at the input of the PD the optical power becomes

$$P_{0,r}(t) = G_{fiber}P_{0,t}(t) \quad (3)$$

Here, $P_{0,t}(t)$ is the optical output of the Mach-Zehnder modulator.

Disregarding all noise in the link, the received signal generated by a photodetector (PD) driving a load of R_L ohms is [2]

$$v'_r(t) = R_L(R_{PD}G_{fiber}P_{0,t}(t) + N_r(t)) \quad (4)$$

where R_{PD} is the responsivity of the PD expressed in units of amps/watt (A/W), $N_r(t)$ is the noise in the received optical signal arising from relative intensity noise and other sources as well as noise generated at the PD itself and R_L is the load at PD. PD noise sources include thermal noise, shot (or quantum) noise, dark current and surface leakage current.

The relationship between the electric field E_{in} of the lased light input to the Mach-Zehnder modulator and the output electric field E_{out} is [3]

$$E_{out} = E_{in}\cos(\pi\frac{\hat{v}}{v_\pi})\exp(j\pi\frac{\overline{v}}{v_\pi}) \quad (5)$$

where $\hat{v} = \dfrac{v_1(t) - v_2(t)}{2}$

and $\overline{v} = \dfrac{v_1(t) + v_2(t)}{2}$

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Here, $v_1(t)$ and $v_2(t)$ are the time-varying electrical signal applied to each electrode, v_π is the extinction voltage of the modulator and a constant bias voltage is applied to one electrode which is for RoF applications expressed as

$$V_{bias} = \frac{Kv_\pi}{2} \qquad (6)$$

Here, K is an integer.

Since the power of an electromagnetic (EM) wave is proportional to the square of the magnitude of its electric field, the optical power at the output of the Mach-Zehnder modulator is

$$P_{0,t}(t) \; \alpha \; \left|E_{out}^2\right|$$
$$\alpha \; E_{in}^2 \cos^2(\pi \frac{\hat{v}}{v_\pi}) \qquad (7)$$

When a Mach-Zehnder modulator is optimally biased and driven by complementary small-signal inputs, substituting Equations (5) and (6) into Equation (4) gives the electrical output of the link as a function of the electrical input as

$$v'_r(t) = (K_1(\cos(\pi(\frac{2s_t(t)}{v_\pi} - \frac{1}{2})) + 1) + N_r(t)R_L$$
$$= (K_1(\sin(2\pi(\frac{s_t(t)}{v_\pi}) + 1) + N_r(t))R_L \qquad (8)$$

Here K_1 is the proportionality constant. By ac coupling, dc offset can be removed and the final expression can be written as

$$v_r(t) = K_1(\sin(2\pi(\frac{s_t(t)}{v_\pi}))) + N_r(t)R_L \qquad (9)$$

Thus, $s(t)$ is transmitted to the analog RoF link which uses a Mach-Zehnder modulator and finally expanding the sin term of equation (9) into Taylor series, the electrical output of the optical link becomes

$$v_r(t) = K_1(\pi(\frac{2s_t(t)}{v_\pi}) - (\pi(\frac{2s_t(t)}{v_\pi}))^3/3! + (\pi(\frac{2s_t(t)}{v_\pi}))^5/5! - ....$$
$$+ (-1)^n (\pi(\frac{2s_t(t)}{v_\pi}))^{(2n+1)}/(2n+1)! + ...) + R_L N_r(t) \qquad (10)$$
$$= K_2 s_t(t) + P_{NL}(t) + R_L N_r(t)$$

$K_2 = (2K_1\pi)/v_\pi$ and $P_{NL}(t)$ is the nonlinear distortion contributed by all of the terms in the Taylor expansion of order greater than unity.

The system output as found in equation (10) will now be used to determine the distortion effects in terms of mean-squared error (ME) and

also pre-distortion functions will be applied to mitigate the distortions. In each case, the simulation results are followed with discussion to analyze the performance.

3. COMPARED ME PERFORMANCE

3.1 ME calculation

The distorted output signal of equation (10) is used for the computer simulation. Input SNR is kept fixed and the average carrier amplitude $C_{carrier}$ of OFDM input signal $s(t)$ is sent through a range of levels.

The ME of one OFDM symbol's normalized constellation can be expressed as

$$ME = \frac{1}{N}\sum_{k=0}^{N-1}\left|EVM(k)\right|^2 \qquad (11)$$

where $\left|EVM(k)\right|$ is the error vector magnitude and

$$\left|EVM(k)\right| = \left|d_r(k) - d_t(k)\right| \qquad (12)$$

Here, k is the subcarrier index and $d_r(k)$ and $d_t(k)$ are the received and transmitted data symbols respectively.

Modulator Index of Mach-Zehnder modulator can be expressed as

$$\Gamma_{MZM} = \frac{C_{carrier}}{(v_\pi/2)} . \qquad (15)$$

3.2 Simulation and results

Using the equations for ME and modulator index as in (11) and (15), the performance of the proposed system is compared with the single carrier based RoF link to finally evaluate the distortion experienced in our proposed system.

The simulation parameters used in this simulation are listed in Table 1 shown above. Initially, signal degradation due to Mach-Zehnder in terms of ME is plotted in Figure 2 against modulator index for OFDM signal based RoF link in our system.

The dashed line in the plot represents constellation ME of undistorted signal with an SNR of 20 dB. From the Figure 2, it is clear that the modulation indices increase due to increase in Γ_{MZM}. Eventually after unity value of Γ_{MZM}, it exhibits change at a rate that is function of both modulation index and the instantaneous amplitude at that particular instant. So, the average amplitude increases with higher PAPR as the modulation index and the instantaneous amplitude are based on average amplitude.
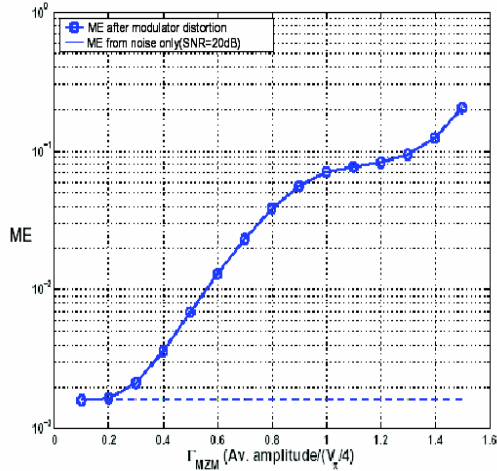

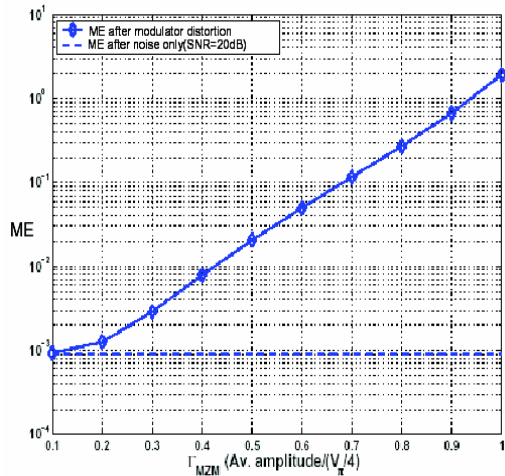Figure 2. Mach-Zehnder Modulator Distortion on OFDM signal

Figure 3. Mach-Zehnder Modulator Distortion on single carrier signal

A time domain single carrier 16-QAM signal is used replacing OFDM signal under similar environment with using raised cosine filtering to allow the signal occupy the same bandwidth as OFDM signal. The plot is shown in Figure 3 in this case. The undistorted ME in this case is 9.2×10^{-4} shown by the dashed lines in the plots which was previously 1.6×10^{-3} in the OFDM signal case as in Fig. 2. Also, the slope of the time-domain curve at unity value of Γ_{MZM}, increases in this case unlike in the OFDM case.

In the presence of Mach-Zehnder modulator distortion, frequency domain equalization techniques seem to the reason for OFDM to show superior performance than the single carrier case. Pre-distortion techniques now will be employed to better performance of OFDM systems.

Table 1. Simulation Parameters

Parameter	*Value*
OFDM Data Rate	12 MSymbol/s
Number of Subcarriers	64
Carrier Frequency	5.8 GHz
Subcarrier Frequency Separation	312.5 KHz
Voltage Extinction Ratio of Mach-Zehnder Modulator	4.5 V
Fiber Path Loss	0.5 dB/km
Fiber Length	5 km- 6 km
Responsivity of the Photo Detector	1 A/W
Photo Detector Load	50 Ω

4. COMPARED PRE-DISTORTION TECHNIQUES

4.1 Pre-distortion function

Generally, to mitigate the non-linear distortion, pre-distortion techniques are used. Hence, in our proposed system, a pre-distortion function $f_{pre}(V)$ is applied to the optical link input voltage to linearize the link and thus to produce a pre-distorted Mach-Zehnder modulator input voltage

$$V_{MZ,\,pre} = f_{pre}(V) \tag{13}$$

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The output of the pre-distortion function is hard-limited so that $|V_{MZ,pre}| = V_{in,peak}$. Otherwise, transfer function of the Mach-Zehnder modulator would cause the output to decrease in response to the increase in V_{in}. So, after applying hard-limiting and letting $V_{in,peak} = |V_{in}|_{max}$, the pre-distortion function can be written as,

$$f_{pre}(V) = \frac{v_\pi}{\pi} \sin^{-1}(\frac{2Sl_{lin}V_{in}}{P_{o,L}}) \quad |V_{in}| \leq V_{in,peak}$$
$$= -V_{in,peak} \qquad V_{in} < -V_{in,peak}$$
$$= V_{in,peak} \qquad V_{in} > V_{in,peak} \qquad (14)$$

The pre-distortion function of equation (14) is used to the OFDM input signal for the computer simulations before the input signal is distorted by Mach-Zehnder modulator. And the performance of the pre-distorted signal is then compared with the signal which was not subjected to pre-distortion i.e. original signal which is modulated without any pre-distortion.

In order to exploit better pre-distortion techniques, the experiments were done under nominal biasing and offset biasing pre-distortion techniques. In the nominal biasing technique, the Mach-Zehnder modulator is biased at $V_{bias,nom} = \frac{V_\pi}{2}$. In this particular point, the transfer function of the modulator exhibits linear behaviour and thus provides the best power efficiency. In the later offset biasing technique, $V_{bias,off}$ is set to zero to hard-clip the signal at its original level. In this approach, the main intention is to clip the passband signal at dc level so that the signal is recovered without any distortion by applying a band-pass filter to remove all out-of- band distortions [6].

In each technique, no noise was taken into account in the simulations to observe the effects of the pre-distortion techniques on the system.

4.2 Simulation and results

Figure 4 shows the results for the nominally biased pre-distorted signal with the original signal without any pre-distortion. Similar results are shown in Figure 5 for offset biasing technique.

For lower values of Γ_{MZM}, as can be seen from Figure 4, both curves remain constant at a value near to 10^{-3}. For the original signal, constellation degradation starts due to Mach-Zehnder modulator distortion effects at a value near to $\Gamma_{MZM} = 0.4$. But for the pre-distorted one, degradation starts from $\Gamma_{MZM} = 0.45$. For values greater than $\Gamma_{MZM} = 0.5$, ME for pre-distorted curve rapidly exceeds than that of original signal curve. The small improvement is therefore observed using the pre-distorted curve in the range of $\Gamma_{MZM} = 0.35$ to 0.5, which is not of that much use to mitigate the mean-square error experienced due to Mach-Zehnder modulator nonlinear distortion.

But if the dc component is removed from the receiver, using this technique can offer a power gain of more than 3 dB when $\Gamma_{MZM} = 0.5$ as can be seen in Figure 6. So, the only usefulness that can be extracted from this technique is to boost received SNR.

On the other hand, until $\Gamma_{MZM} > 0.9$, the pre-distorted signal does not begin to degrade
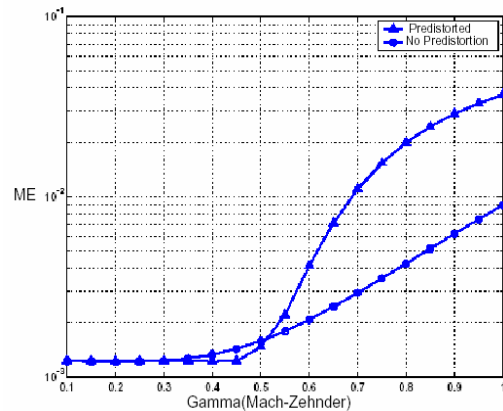

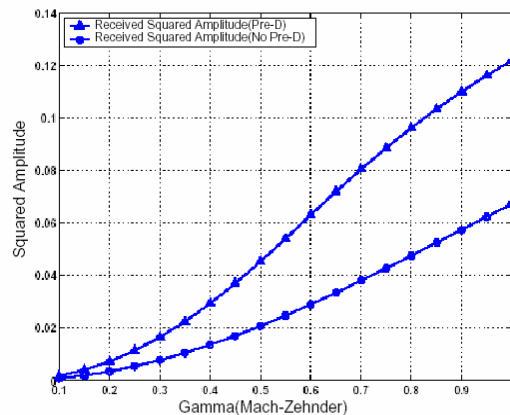Figure 4. Mean Square error curves using nominal Mach-Zehnder modulator biasing technique

Figure 5. Received squared amplitude power at nominally biased point

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when offset biasing technique is used as can be seen from the Figure 5. And, the constellation error is less in the pre-distorted signal curve than that of original signal curve by almost an order of magnitude. Also, the error in this case is far below than that of original curve in the Figure 4 where nominal biasing was used. Therefore, a distortion-free dynamic range of more than 6dB can be enjoyed using offset biasing technique.

With the increase of Γ_{MZM}, power of the pre-distorted signal input decreases. But the reverse happens to power of the original signal. Previously, in the nominal biasing case, power of the pre-distorted input power increased at a higher rate than original signal. The ac power output from the PD which is proportional to the received square amplitude is shown in the Figure 7. At
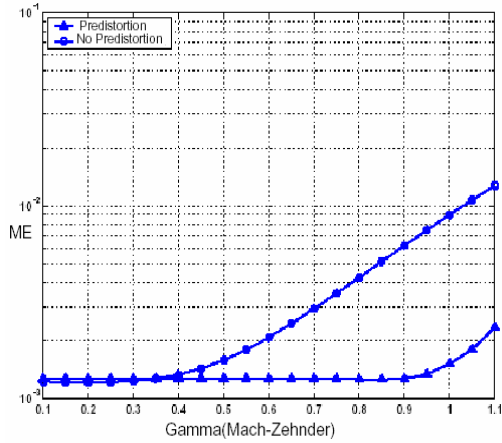

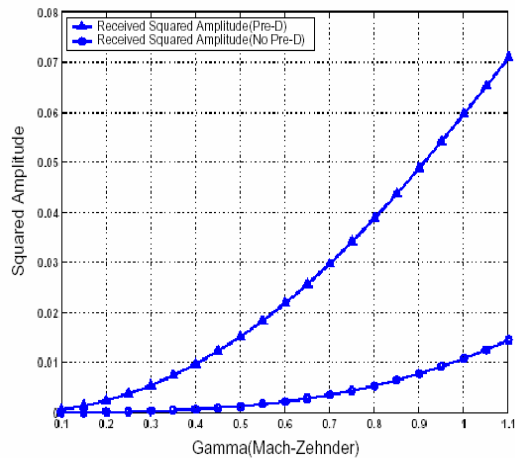Figure 6. Mean Square error curves using offset Mach-Zehnder modulator biasing technique

Figure 7. Received squared amplitude power at offset biased point

Γ_{MZM} =0.5, squared amplitude of the undistorted original signal is 10^{-3}, which is much smaller than that of nominally biased value. But for the offset pre-distorted signal, at Γ_{MZM} =0.9, the squared amplitude is 0.05, which is 4 dB more than that of the nominally biased case. So the distortion-free dynamic region is more here.

So, finally, the offset biasing pre-distortion technique has the potential to increase both the distortion-free dynamic range and the SNR of the Mach-Zehnder based optical link.

5. CONCLUSION

It has been found that, with increasing Mach-Zehnder modulator input levels, the rate of increase in nonlinear distortion for OFDM is much lower than that of single-carrier systems. And also, if pre-distortion techniques are applied, offset biasing technique offers better advantages in terms of distortion-free dynamic range and SNR. This work will eventually help to design an OFDM based RoF link at 5.8 GHz frequency employing Mach-Zehnder modulator for the microcell and picocell applications in future networks. Hence, it will be possible to implement ubiquitous networks economically if suitable offset biasing pre-distortion is applied for OFDM-RoF links to eventually receive more output power. A similar research is being carried out to employ IEEE 802.16a standard for long-haul outdoor wireless links as 802.16a is more tolerant than 802.11a in terms of the delay spreads and propagation times.

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