Degradation of ICI in OFDM communication system by analyzing I/Q Imbalance and Impact of Timing jitter.

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Abstract: *In the high data rate orthogonal frequency division multiplexing (OFDM) systems has the problem of intercarrier interference (ICI) because of Timing jitter and I/Q imbalance, owing to this bit error rate increased. It proposed a new algorithm to analyze the interaction between timing jitter and I/Q imbalance which produce the extra ICI terms in their interaction. This analysis indicates that intercarrier interference (ICI) has equal real and imaginary components and is independent of received subcarrier index. Moreover it is shown that the parameters values impact the intercarrier interference (ICI)from the relative contribution on timing jitter and I/Q imbalance, timing jitter taking over for larger jitter values and I/Q imbalance dominating when timing jitter is relatively small. The interaction is negligible for extra ICI in all cases. The standard experimental results are best matched with the analytical proposed result.*

Key words*: - OFDM (orthogonal frequency division multiplexing),I/Q imbalance, Timing jitter, ICI(Inter carrier interference).*

Introduction

Orthogonal Frequency Division Multiplexing (OFDM). In a various wireless standards such as digital video broadcasting (DVB-T), digital audio broadcasting (DAB), the IEEE 802.11a local area networks (LAN) standard and the IEEE 802.16a has been used OFDM scheme [1-2]. In the optical fiber systems data rates are very high, for example the transmission of 121.9 Gbits/s within an optical bandwidth of 22.8GHz has been shown up [3]. For the very high data rates, the OFDM systems need high speed digital to analog converters (DACs) and analog to digital converters (ADCs) using accurate sampling clocks, however the signal edges of the Practical sampling clocks vary from the ideal position and these fluctuate are stated as timing jitter. The performance of the OFDM system is limited by timing jitter this has been analyzed in recent times [4-7].The timing jitter causes noticeable performance degradation in high frequency band pass sampling receivers and mitigation techniques [4]. An upper bound for the interference caused by timing jitter is derived and the effects of integer oversampling are studied [5]. A large analysis of timing jitter is presented including the effect of both white and colored timing jitter by a timing jitter matrix which describe the rotational and intercarrier interference (ICI) effect of timing jitter in OFDM systems and applied this matrix to show that both fractional oversampling and integer oversampling can be used to reduce the ICI power due to timing jitter [6-7]. I/Q imbalance appears when a front-end component doesn't respect the power balance or the orthogonality between the I and Q branch[9]. While being able to easily cope with the frequency selective nature of a multi-path propagation channel, multi-carrier systems are very sensitive to I/Q imbalance [10]. In order to cope with these impairments, numerous approaches for a digital compensation of the I/Q imbalance have been proposed [11].

System Model

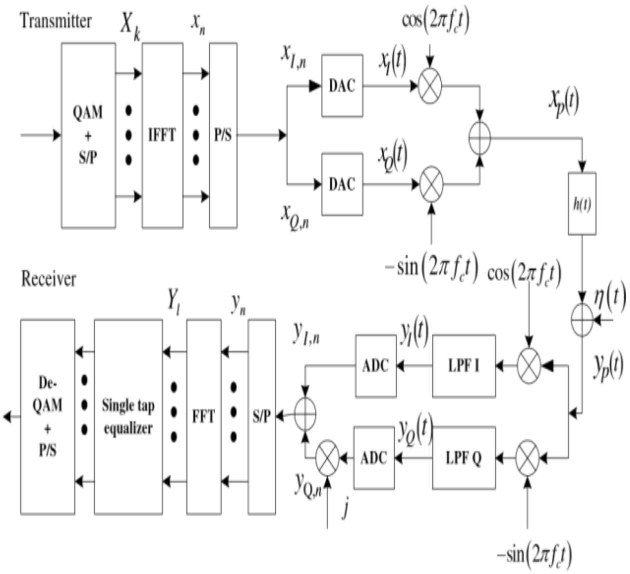


Fig. 1. Simplified OFDM block diagram

Consider the OFDM system shown in Fig. 1. There are N subcarriers and the OFDM symbol period, not including the cyclic prefix (CP), is T. At the transmitter, incoming binary stream of data is rearrange into parallel blocks for digital modulation and further processing. Parallel data mapped from bits symbol according to the selected modulation scheme. (16 QAM,BPSK,QPSK)The data to be transmitted in each OFDM symbol period is represented by complex vector X of length N. In most OFDM systems the band-edge subcarriers are not used, so some of the elements of X are zero.In (IFFT)Section each group of symbol is move from frequency domain to time domain. The complex time domain samples at the output of the transmitter inverse fast Fourier transform (IFFT) are given by

$$x_n = \frac{1}{\sqrt{N}} \sum_{k=-\frac{N}{2}+1}^{N/2} X_k \exp\left(\frac{j2\pi nk}{N}\right). \qquad (1)$$

By using DACs, the real and imaginary parts of the digital baseband

$$x_I(t) = \mathrm{Re}\left\{\frac{1}{\sqrt{N}} \sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} X_k \exp\left(\frac{j2\pi tk}{T}\right)\right\} \qquad (2)$$

$$x_Q(t) = \mathrm{Im}\left\{\frac{1}{\sqrt{N}} \sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} X_k \exp\left(\frac{j2\pi tk}{T}\right)\right\} \qquad (3)$$

signal xn are converted to analog baseband signals given by where xI(t) and xQ(t) denote the real and imaginary parts of analog baseband signal and Re{·} and Im{·} are the real and imaginary parts of the argument. xI(t) and xQ(t) are subsequently combined by an I/Q mixer, which we assume to be ideal, to give the passband transmitted signal

$$x_p(t) = x_I(t)\cos(2\pi f_c t) - x_Q(t)\sin(2\pi f_c t)$$
$$= \mathrm{Re}\{x(t)\exp(j2\pi f_c t)\}, \qquad (4)$$

where fc is the RF or optical carrier frequency, and x(t) =

xI(t) + j · xQ(t).

At the receiver, the received signal is

yp(t) = xp(t) ⊗ hp(t) + ηp (t), (5)

where ηp(t) is bandpass AWGN and hp(t) is bandpass channel impulse response. Note that xp(t), yp(t), ηp(t) and hp(t) are all real, while all the baseband signals such as Xk, xn,Yk, yn, xI,n, xQ,n, yI,n and yQ,n, baseband channel impulse response, h(t), and baseband AWGN, η(t), are all complex.In receiver section we used quadrature demodulation and low pass filter for perfect matching between Real(I) and Imagnary (Q) branches. The received signal yp(t) result in baseband I and Q components yI(t) and yQ(t) given by

yI(t) = LPF{cos(2πfct) · yp(t)} (6)
= Re{x(t) ⊗ h(t) + η(t)},
yQ(t) = LPF{−sin(2πfct) · yp(t)} (7)
= Im{x(t) ⊗ h(t) + η(t)},

where LPF{·} represents the low-pass filtering. The quadrature down-converted signals are sampled by I and Q branch ADCs and these each introduce timing jitter [13]. We assume the timing jitter in the I branch is the same as timing jitter in the Q branch. The signal samples after the two ADCs are given by

$$y_{I,n}(t) = \mathrm{Re}\left\{\frac{1}{\sqrt{N}} \sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} H_k X_k \exp\left(\frac{j2\pi tk}{T} + \tau_n\right) + \eta_n\right\} \qquad (8)$$

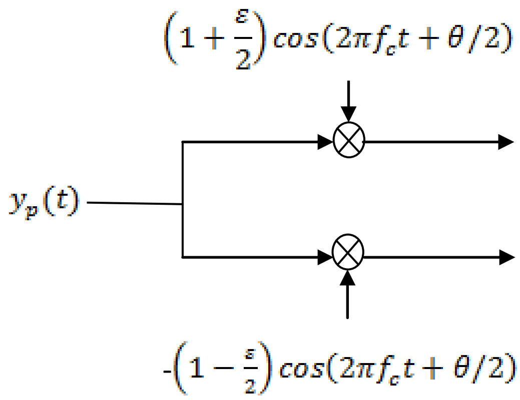


Fig 2. Quadrature down-converter with I/Q amplitude and phase imbalance.

$$y_{Q,n}(t) = \mathrm{Im}\left\{\frac{1}{\sqrt{N}} \sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} H_k X_k \exp\left(\frac{j2\pi tk}{T} + \tau_n\right) + \eta_n\right\} \qquad (9)$$

where τn is the discrete timing jitter and Hk is the discrete frequency domain channel response of the kth subcarrier. The resulting complex samples at the input to the FFT are

yn = yI,n + j · yQ,n. (10)

In any practical system, perfect matching between I and Q branches is not possible due to limited accuracy in the implementation of the RF or optical front-end. In this paper, we consider only the I/Q imbalance at the receiver side. I/Q imbalance can be modeled as either symmetrical or asymmetrical. Both models are equivalent representations [14]. We will use the symmetrical model in this paper. In the symmetrical model [9], each arm experiences half of the phase and amplitude imbalance as shown in Fig. 2. Assume that there is a phase imbalance of θ degrees and an amplitude imbalance of δ dB and that θ and δ are frequency independent. In this case, the FFT output is given by [7]

$$Y_l = \alpha \frac{1}{\sqrt{N}} \sum_{n=-\frac{N}{2}+1}^{N/2} y_n \exp\left(\frac{-j2\pi nl}{N}\right) + \beta \frac{1}{\sqrt{N}} \sum_{n=-\frac{N}{2}+1}^{N/2} y_n^* \exp\left(\frac{-j2\pi nl}{N}\right) \qquad (11)$$

With

$$\alpha = \cos(\theta/2) + j(\varepsilon/2)\sin(\theta/2) \qquad (12)$$

$$\beta = (\varepsilon/2)\cos(\theta/2) - j\sin(\theta/2) \qquad (13)$$

Where the superscript * denotes the complex conjugate and $\frac{\varepsilon}{2} = \left(10^{\frac{\delta}{10}} - 1\right) / \left(10^{\frac{\delta}{10}} + 1\right)$

TIMING JITTER ANALYTICAL AND I/Q IMBALANCE ANALYSIS

In this section of the paper, it is indicated that due to timing jitter in the received signal, the noise as ICI components are added. We originate the ICI power caused by I/Q imbalance and timing jitter. Altering (11) into the compact matrix form

$$Y = \alpha WHX + \beta WH^{*}X_m^{*} + N, \qquad (14)$$

where

$$Y = \left[Y_{-\frac{N}{2}+1} \cdots Y_0 \cdots Y_{\frac{N}{2}} \right]^T.$$

$$X_m^{*} = \left[X_{\frac{N}{2}}^{*} \cdots X_0^{*} \cdots X^{*}_{-\frac{N}{2}+1} \right]^T,$$

$$W = \begin{bmatrix} w_{-\frac{N}{2}+1,-\frac{N}{2}+1} & \cdots & w_{-\frac{N}{2}+1,\frac{N}{2}} \\ \vdots & \ddots & \vdots \\ w_{\frac{N}{2},-\frac{N}{2}+1} & \cdots & w_{\frac{N}{2},\frac{N}{2}} \end{bmatrix},$$

$$N = \left[N_{-\frac{N}{2}+1} \cdots N_0 \cdots N_{\frac{N}{2}} \right]^T$$

The elements of X_m^{*} are the complex conjugate of the transmitted signal's mirror image. The elements of W are given by

$$w_{l,k} = \frac{1}{N} \sum_{n=-\frac{N}{2}+1}^{N/2} \exp\left(\frac{2\pi k}{T}\left(\frac{nT}{N} + \tau_n\right)\right) \exp\left(\frac{-j2\pi nl}{N}\right). \qquad (15)$$

In the received signal both timing jitter and I/Q imbalance cause added noise like components. From (14)

$$Y = \alpha HX + \underbrace{\alpha(W - I)HX\beta + WH^{*}X_m^{*} + N}_{} \qquad (16)$$

ICI due to both timing jitter and I/Q imbalance

Substitute the value of (12) into the first component of the right hand side of (16), we obtain

$$Y = \cos\left(\frac{\theta}{2}\right)HX + j\left(\frac{\varepsilon}{2}\right)\sin\left(\frac{\theta}{2}\right)HX + \alpha(W - I)HX + \beta(W - I_m)H^{*}X_m^{*} + \beta H^{*}X^{*} + N \quad (17)$$

Where I_m is the mirror image of I. We are pondering a unity gain flat channel so $H_k = 1$. In order to recover the transmitted signal, both sides of (16) are scaled by $\cos\left(\frac{\theta}{2}\right)$ to give

$$\frac{Y}{\cos\left(\frac{\theta}{2}\right)} = X + j\left(\frac{\varepsilon}{2}\right)\tan\left(\frac{\theta}{2}\right)X + \frac{\alpha}{\cos\left(\frac{\theta}{2}\right)}(W - I)X + \frac{\beta}{\cos\left(\frac{\theta}{2}\right)}(W - I_m)X_m^{*} + \frac{N}{\cos\left(\frac{\theta}{2}\right)}, \qquad (18)$$

Where X is a wanted component From (15) and (17), we obtain

$$\frac{Y_l}{\cos(\theta/2)} = X_l - j\tan\left(\frac{\theta}{2}\right)X_l^{*} + \left(\frac{\varepsilon}{2}\right)X_l^{*} + j\left(\frac{\varepsilon}{2}\right)\tan\left(\frac{\theta}{2}\right)X_l + (w_{l,k} - I_{l,k})X_l + j\left(\frac{\varepsilon}{2}\right)\tan\left(\frac{\theta}{2}\right)$$
$$+ \left(\frac{\varepsilon}{2}\right)(w_{l,k} - I_{l,-k})X_{-l}^{*} - j\tan\left(\frac{\theta}{2}\right)(w_{l,k} - I_{l,-k})X_{-l}^{*} + \frac{N_l}{\cos\left(\frac{\theta}{2}\right)} \quad \ldots (19)$$

In the equation 19 right hand side, all the components except the X_l component are noise and ICI components related to various impairments. Timing jitter, I/Q imbalance and AWGN is the outcome of their impairments. At the rear of, we look into the consequences of the both I/Q imbalance and timing jitter in a noiseless channel. Due to I/Q imbalance and timing jitter are independent of the subcarrier index, the average ICI power for each subcarrier is the same as the average ICI power. First, consider the contribution to ICI set off by the interaction between jitter and I/Q imbalance. This is given by the 6th, 7th and 8th components on the right hand side of (19). The ICI power Due to these is

$$P_{jitter+\theta+\varepsilon} = E\left\{\left| j\left(\frac{\varepsilon}{2}\right)\tan\left(\frac{\theta}{2}\right)\sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} (w_{l,k} - I_{l,k})X_k \right|^2\right\}$$
$$+ E\left\{\left|\left(\frac{\varepsilon}{2}\right)\sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} (w_{l,k} - I_{l,-k})X_{-k}^{*}\right|^2\right\}$$
$$+ E\left\{\left| -j\tan\left(\frac{\theta}{2}\right)\sum_{k=-\frac{N}{2}+1}^{\frac{N}{2}} (w_{l,k} - I_{l,-k})X_{-k}^{*}\right|^2\right\}. \quad (20)$$

The timing jitter is white which we take up i.e, the correlation between different timing jitter samples is zero. By using the [5] method which applies a Taylor series expansion, (20) can be simplified to give

$$P_{jitter+\theta+\varepsilon} = \frac{\sigma_S^2\sigma^2}{6}\left(\left(\frac{\varepsilon}{2}\right)^2\tan^2\left(\frac{\theta}{2}\right) + \left(\frac{\varepsilon}{2}\right)^2 + \tan^2\left(\frac{\theta}{2}\right)\right)\left(\frac{N\pi}{T}\right)^2. \quad (21)$$

Thus the ratio of the total ICI power (selecting in all componets) to signal power ratio from (19) and (21) is given by

$$\gamma = \frac{P_{total}}{\sigma_S^2}\left\{\left(1 + \left(\frac{\varepsilon}{2}\right)^2\tan^2\left(\frac{\theta}{2}\right) + \left(\frac{\varepsilon}{2}\right)^2 + \tan^2\left(\frac{\theta}{2}\right)\right) \times \frac{1}{6}\pi^2\bar{\sigma}_j^2\right\} + \tan^2\left(\frac{\theta}{2}\right) + \left(\frac{\varepsilon}{2}\right)^2 + \left(\frac{\varepsilon}{2}\right)^2\tan^2\left(\frac{\theta}{2}\right), \quad (22)$$

Where $\bar{\sigma}_j = \sigma_j N/T$ is the normalized standard deviation(SD) of the timing jitter.

Experimental Result

In this section, the impairments caused by timing jitter and I/Q imbalance are examined through computer simulations, to verify the derived analytical results. We use a system with N = 512 subcarriers, a flat channel and 2000 OFDM symbols. The ICI is calculated based on the spreading of constellation points [15].

We examine the combined effect of I/Q imbalance and timing jitter. The timing jitter and IQ imbalance values are very system dependent [15]. Fig. 3 shows the effect on the ICI to signal power ratio, γ, of varying phase imbalance and timing jitter when there is no amplitude imbalance. Fig. 4 shows the simulation and analytical results for varying amplitude imbalances and timing jitter when there is no phase imbalance, while Fig. 5 gives results for a range of combinations of amplitude and phase imbalances and timing jitter. Fig. 3 (no amplitude imbalance) shows that for σ¯j <0.01, the ICI depends strongly on the phase imbalance, but that as timing jitter levels increase, the effect of timing jitter dominates and increasing the phase imbalance has only a small effect.

Fig. 3. γ versus the phase imbalance with σ¯j =0,0.01,0.03,0.06,0.1 and δ =0 dB.

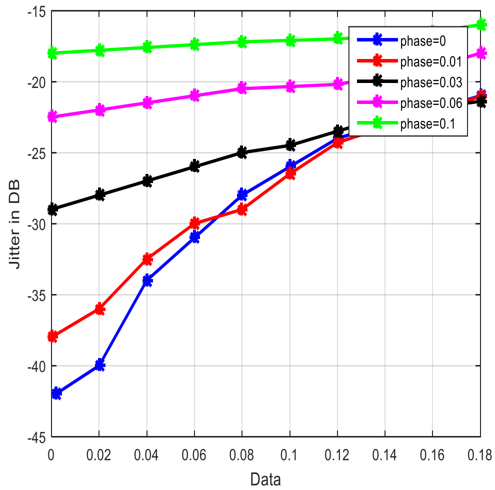


Fig. 5. γ versus timing jitter with I/Q imbalance.

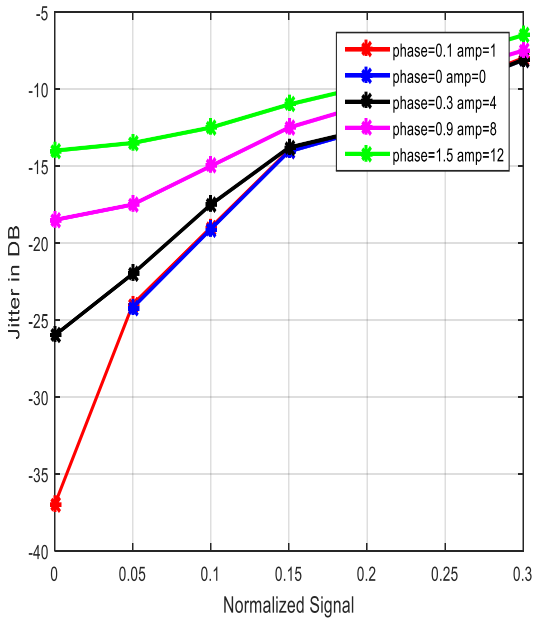
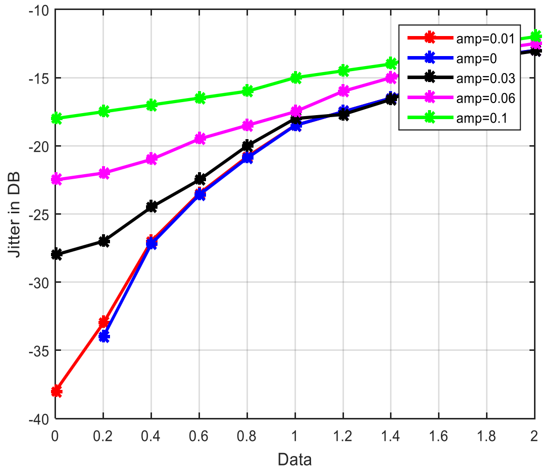


Fig. 4. γ versus the amplitude imbalance with σ¯j =0,0.01,0.03,0.06,0.1 and



(no phase imbalance) shows a similar effect. For σ¯j <0.01, the ICI depends strongly on the amplitude imbalance, but as timing jitter increases the effect of timing jitter dominates. The simulation results agree with analytical results given in (22). Fig. 5 shows the average ICI to signal power ratio against the timing jitter with both phase and amplitude imbalance. When θ = 1◦ and δ = 0.1 dB, there is very little increase in ICI power compared with the plot without I/Q imbalance.

However even when θ = 12o and δ = 1.5 dB, and for σ¯j >0.15, the ICI power increase is not significant compared with the plot without I/Q imbalance. This indicates that timing jitter introduces more ICI power than I/Q imbalance.

Conclusion

In this paper, we analyze the impact of timing jitter and I/Q imbalance in OFDM systems. It is shown that both timing jitter and I/Q imbalance introduce ICI at the receiver and can cause severe performance degradation in OFDM systems. When I/Q imbalance is considered, more ICI components are added. These ICI components are not only caused separately by phase and amplitude imbalance but also jointly by timing jitter and I/Q imbalance. It is also shown that the relative contribution of I/Q imbalance and timing jitter to ICI depend on the parameter values, with I/Q imbalance dominating when timing jitter is relatively small and timing jitter dominating for larger jitter values. In all cases the extra ICI caused by the interaction is negligible.

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