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Mitigating Phase Noise Effects in Orthogonal Frequency Division Multiplexing System Using Phase Locked Loop

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Abstract— Orthogonal Frequency Division Multiplexing System are better suited to the today's generation 3G networks and upcoming 4G networks in terms of bandwidth efficiency due to overlapping of frequency bands, high speed data transfer due to parallel data transfer, maintaining high quality of wireless link even under multipath conditions due to low symbol rate it minimizes ISI effects. The application of channel codes like convolution codes further reduces the Bit Error Rate and improves the link reliability. Although OFDM systems shows superior performance over single carrier and FDM system but there is one disadvantage that is the over sensitivity to Phase noise of the local oscillator which hinders the orthogonality of the sub carriers and increases inter carrier interference. OFDM system performance is degraded due to phase noise. Accordingly going deep into the various parameters of the OFDM system it was observed that Phase Locked Loop (PLL) could better control the phase noise problem in comparison to free running oscillator. It is deployed at the downlink side of incoming signal received from Antenna generating its own local frequency slightly higher than the incoming frequency to generate IF signal (after mixing the incoming and the local frequency) for further processing. Accordingly to examine closely the other aspects of PLL in relation to Free Running Local Oscillator various parameters of PLL in relation to OFDM system were studied in detail.

Index Terms— Bit Error Rate; Signal to Noise Ratio; Phase Locked Loop; Power spectral densities.

I. INTRODUCTION

Nowadays, however, the effects of phase noise can be much more severe, since the used waveforms are getting more complex (and thus sensitive to any additional distortion), and also because less receiver selectivity is typically implemented at RF, compared to earlier device implementations. Most emerging radio systems are based on multicarrier modulation, mainly orthogonal frequency division multiplexing (OFDM) or some of its variants. OFDM-type waveforms have generally a fair amount of advantages over the more traditional single carrier signals [1], but there is also price to pay since multicarrier systems are found relatively vulnerable to radio component non idealities, such as phase noise [2]. Phase noise effect on OFDM waveforms, in terms of in-band distortion, is generally twofold [2], [11].

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First of all, it causes rotation of symbol constellation called common phase error (CPE). This effect is very similar to the phase noise effect on single carrier systems, and is thus fairly easily cancelled as we know that OFDM provides a selection of modulation constellations for each carrier. For example, the 802.11a standard provides for individual carrier modulation up to 64 quadrature amplitude modulation (QAM) [3]. Although signal impairments due to multi-path are eliminated through the use of a cyclic prefix guard interval (during which no demodulation is performed in the receiver), the closeness of the constellation points can result in significant errors due to dispersion. This dispersion can be caused by motion of the radio units or from motion of any other object in the channel. It can also be caused by phase variation with frequency in the radio antennas, filters, and other components. [7]

II. PHASE NOISE EFFECTS IN THE QUALITY OF AN OFDM SIGNAL

Phase noise effects in the quality of an OFDM signal will be approached both from a theoretical point of view and simulations. The theoretical analysis will allow us to identify two different kinds of effects that are introduced by phase noise in OFDM signals: common phase error and inter-carrier interference. Simulations will provide error performance results in non ideal situations. The assumptions and simplifications (small phase noise values) made in the analysis to understand the system behaviour have been applied to simulations, so results can be obtained for any phase noise and channel situations. In the following sections phase noise effects in OFDM and single carrier (SC) signals, tolerable phase noise spectrum masks and improvements achieved by phase noise correction are analysed.

A. Theoretical Analysis Of Phase Noise

A theoretical analysis of phase noise effects in OFDM signals can be found in [10]. In order to understand the meaning of the different parameters, this analysis is reproduced here without details: Taking into account, the complex envelope of the transmitted OFDM signal for a given OFDM symbol, sampled with sampling frequency $f_s = B$, is :

$$x(n) = \sum_{K=0}^{N-1} s_k e^{j(2\pi/N)kn}$$

with n = 0,1,….,N-1 (1)

This symbol is actually extended with a Time Guard in order to cope up with multipath delay spread. For the sake of simplicity, we will not consider this prefix since it is eliminated in the receiver.

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Assuming that the channel is flat, the signal is only affected by phase noise Φ (n) at the receiver:

$$r(n) = x(n) . e^{j\Phi(n)} \quad (2)$$

The received signal is Orthogonal Frequency Division Demultiplexed (OFDD) by means of a Discrete Fourier Transform. In order to separate the signal and noise terms , let us suppose that □(n) is small , so that:

$$e^{j\Phi(n)} \approx 1+j\Phi(n) \quad (3)$$

In this case, the demultiplexed signal is:

$$Y(K) \approx S_K + \frac{j}{N}\sum_{r=0}^{N-1} S_R \sum_{n=0}^{N-1} \Phi(N).\, E^{J(2\Pi/N)(R-K)N} \quad (4)$$

$$\mathbf{y(k) \approx s_k + e_k}$$

Thus we have error term e_k for each sub carrier which results from some combinations of all of them and is added to the useful signal. Let us analyse more deeply this noise contribution:

1) *if r = k: Common Phase Error:*

$$\frac{j}{N}\sum_{r=0}^{N-1} s_r \sum_{n=0}^{N-1} \Phi(n) = j.s_k . \Phi \quad (5)$$

A common error added to every sub-carrier that is proportional to its value multiplied by a complex number jΦ, that is a rotation of the constellation.

This angle results from an average of phase noise:

$$\Phi = \sum_{n=0}^{N-1} \Phi(n) \quad (6)$$

This average implies when phase noise bandwidth is less than inter carrier frequency spacing .Since it is constant for all subcarriers , it can be corrected by some kind of phase rotation.

1) *if r ≠ k : Inter-Carrier Interference:*

$$\frac{j}{N}\sum_{r=0}^{N-1} s_r \sum_{n=0}^{N-1} \Phi(n).\, e^{j(2\pi/N)(r-k)n} \quad (7)$$

This term corresponds to the summation of the information of the other N-1 sub carriers each multiplied by some complex number which comes from an average of phase noise with a spectral shift. The result is also a complex number that is added to each sub-carrier's useful signal and has the appearance of Gaussian Noise. It is normally known as Inter carrier Interference (ICI) or loss of orthogonality [9]. The spectral components of phase noise that contributes to the magnitude of error are those from Δ (f) (inter carrier spacing) up to the total phase noise bandwidth. Because of its random nature, it cannot be corrected.

If the phase noise variance in radians $\sigma^2 = 0.1$ rad^2 and the number of OFDM sub-carriers are increased such that initially the ratio of phase noise bandwidth to inter carrier spacing Δ(f) that is B/ Δ(f) = 0.01 and it increased to B/ Δ(f) = 1 , then it shows that ICI dominates over CPE with decrease in sub-carrier frequency spacing or increase in number of OFDM sub-carriers. As this ratio approached unity, that is the phase noise bandwidth becomes closer to the inter carrier spacing value, the inter carrier interference increases and the correction capabilities decreases. [2], [9], [10], [11]

III. CONTROL OF PHASE NOISE IN OFDM SYSTEM

It has been observed that in a practical system, in the context of phase noise, the receiver with implemented PLL has better performance than the one with a free- running oscillator [11]. As the PLL receiver output phase noise is controlled by the filter bandwidth, feedback path , VCO gain its variance σ^2 (when phase noise is modelled as a Gaussian stochastic process with mean phase, $\mu = 0$ radians) is always less than free running oscillator output phase noise variance σ^2, which drifts away freely from the mean phase wherein PLL always tries to lock the original phase with negative feedback of phase error .

The ICI in OFDM system can be significantly controlled by implementing PLL at the receiver which can shape the phase noise power spectral density (dBc) up to the filter bandwidth defined by the cut off frequency (f_c) for the frequency offsets from the reference carrier in comparison to the free running VCO.

A. Transfer Function Of Pll And It's Stability

The filter and the VCO determine the stability of PLL whose transfer function is of second order when filter is of first order. The Low Pass Filter normally used is Butterworth or chebyschev. There are codes which could find the order of Chebyschev filter in reference to pass band ripple, stop band ripple, pass band frequency, stop band frequency and the sampling frequency of the incoming signals to the PLL which have VCO and the filter. Incoming signals may be a IFFT signal of OFDM with 1000 sub carriers within the specified bandwidth and filter for the sake of simplicity may be of first order whose transfer function is $W_c / (s+W_c)$ where s = jw +σ , w = 2*pi*f radians per second while Wc is the Cut off frequency. The transfer function of the PLL is:

$$(TF) = w_n^2/(s^2+2*w_n*\zeta*s+w_n^2) \quad (8)$$

The coefficient w_n is called the natural frequency (not to be confused with carrier or centre frequency; it has nothing to do with that). The natural frequency w_n is a quality of the response of the PLL. The quantity ζ , which is called the damping factor can be used to examine the transient qualities of the loop. As in mechanical system, if proper damping factor is not used, the vibration, error signal in our case, do not damp out and the system become UNSTABLE. The filter is very important in the design of the PLL, since both the natural frequencies and the damping factor are a factor of the filter response. In fact we can say that the design of PLL is almost entirely dependent on the design of the loop filter. [10]

Actual oscillators include noise sources that cause the output frequency to deviate from its ideal position, producing a "skirt" of unwanted frequencies near the carrier.

The output phase noise is shaped by the VCO gain K (vco) having f_o frequency modulated by a noise source of $V_n(f_n)$ in a bandwidth of 1 Hz at Offset fn from the Sub Carrier frequency fo to be approximated using a Narrow Band FM. An Analytical Approach to define a Phase Noise to have VCO output :

$$Vout(t)=Ao*Cos(2*\pi*fo*t)+Ao*Kvco*(Vn(fn)/2fn)*[Cos(2*\pi*fo+2*\pi*fn)t+ Cos(2*\pi*fo- 2*\pi*fn)t] \quad (9)$$

The first term represents the carrier signal, and the second term represents noise power at a +- *fn* offset from the carrier. Phase noise is defined as the ratio of noise power at the f_n offset to the carrier power at f_o:

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$$L(fn) = \left(\frac{KvcoVn(fn)}{2fn} \right)^{\wedge 2} \quad (10)$$

Taking log of this (9) with base 10 will give phase noise power in decibels per hertz within 3 dBc bandwidth of sub carrier frequency f_o.

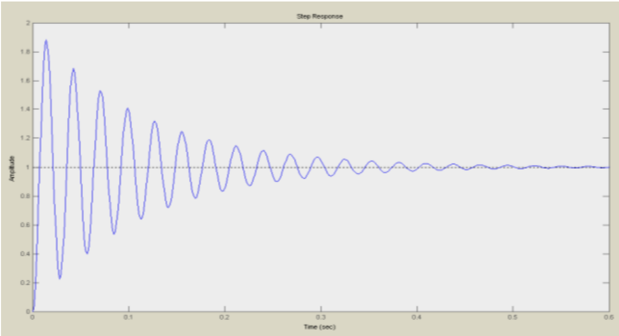

Fig 1 : Time response against a unit step input to a second order PLL which almost stabilizes after 0.3 seconds against damped oscillations The special case of PLL transfer unction wherein ζ = 0.0375, w^2 = (2*pi*40)^2=49600

IV. SIMULATION RESULTS

The simulation results have been obtained using MATLAB which shows that Phase noise causes the linear increase Intercarrier interference (ICI) power amongst the sub carriers with increase in the number of sub carriers

A. Testing orthogonality of ofdm output sub tones from pll with rayleigh channel

The input in the PLL at the downlinks side of OFDM system was taken to be two orthogonal tones and also the amplitudes of these tones was corrupted with multipath Rayleigh channel noise and it could be observed that the resultant output from PLL was not only jerk and free of noise but had maintained the mutual orthogonality between the tones.

The output after taking dot product appears to have zero amplitude indicating maintainability of orthogonality in PLL output while taking two mutually orthogonal sub carriers tones of an OFDM input in the downlink of an OFDM.

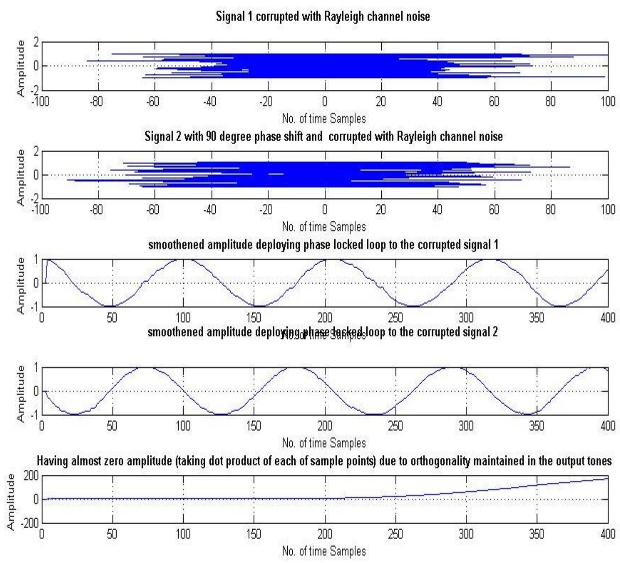

Fig 2: Maintained orthogonality of OFDM output sub tones from PLL with Rayleigh channel

B. ICI Power of Ofdm versus K (Relative Phase Noise Bandwidth)

The inter carrier interference amongst the OFDM sub carriers increases with the increase in the level of degree of closeness, which in turn depends upon inter carrier frequency spacing (in Hertz) and phase noise bandwidth (in dB), the ratio of these two i.e. K = VCO phase noise bandwidth (3dB)/ Sub carriers frequency spacing (Hertz) is the relative Phase Noise bandwidth. [9]

Fig 3: Linear Relation of OFDM Subcarrier interference Power with K

C. SNR degradation with increase of relative vco phase noise bandwidth

Fig. shows SINR after OFDM demodulation for SNRo[dB]=20dB, 30dB. For both the SNR values SINR is plotted for the cases when the VCO is used either as a free running oscillator or within a PLL. As expected the SINR is reduced when increasing the phase VCO phase noise bandwidth . On the other hand it can also be observed , that regarding performance due to phase noise there is almost no difference if PLL is used or not as the curves with PLL lie only slightly above the ones for the free running oscillator

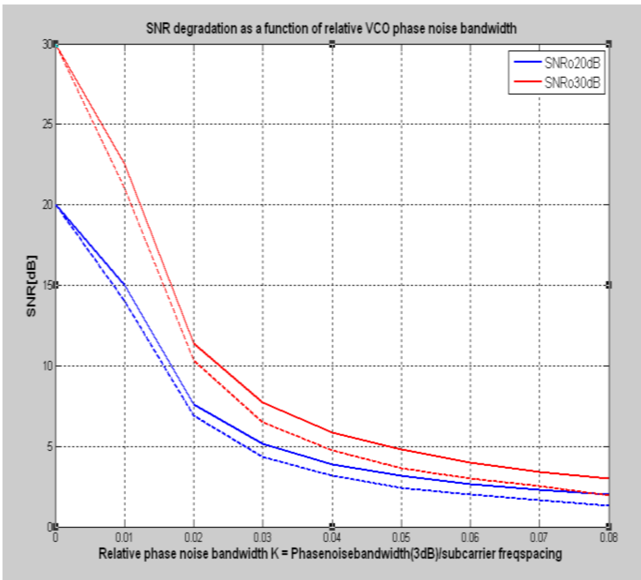

Fig 4: SNR degradation as a function of relative Phase Noise bandwidth

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D. Power Spectrum Of Phase Noise For Free Running And Pll Oscillator Against Frequency Offset From Reference Carrier Frequency In Hertz

The PLL Phase noise power spectrum appears to be shaped in comparison to free running local oscillator. Note that the spectrum of ΦPLL(t) is basically a low pass filtered version of the spectrum of ΦFree(t).

The advantage of using a PLL lies in the fact that it shapes the phase noise spectrum at low frequencies which determines the amount of the' Common Phase Error ' power . On the other hand the phase of a 'free running oscillator' can freely drift away from the reference signal phase thus the mean ΦFree(t) which is equivalent to the correction of the Common Phase Error can take virtualy any value for ONE OFDM SYMBOL.

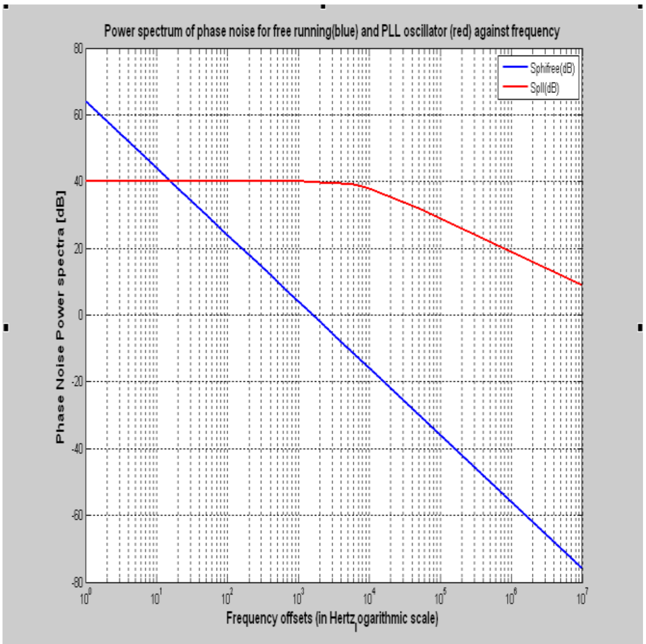

Fig 5: Power spectrum of Phase noise for Free running Oscillator versus Phase Locked Loop (PLL)

PLL is tracking the phase of an input signal so Φpll(t) will oscillate around zero. The Φpll(t) is an ornstein-uhlenbeck process[1] which has the tendency of coming back. Thus considering 'phase noise' in the context of OFDM , a pll can rather be seen as a cpe (common phase error) filter. In this context different pll topologies (may perhaps a charge pump pll) can be further used to diminish the influence of cpe

V.CONCLUSION

The effect of a phase noise on a OFDM system with parameters typical for today's OFDM based WLAN standards has been studied. System performance was compared when the local oscillator at the receiver is realized as a PLL using orthogonality test which shows that the performance of PLL is exalted in so far as phase locking is concerned, for different channel conditions. PLL has the ability to shape the Phase noise power spectra defined by the cut off frequency of the loop filter. The order of the loop filter determines the stability of the PLL. As observed from the simulation results BER of PLL is always less than the ordinary local oscillator even with decrease in sub carrier spacing.

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