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Characterization of MUI for OFDMA Uplink in Presence of Transceiver Phase Noise

Kamayani Shrivastav[1*] and R. P. Yadav[2]
[1,2]Department of Electronics and Communication, Malaviya National Institute of Technology, Jaipur, India
[1]2014rec9012@mnit.ac.in, [2]rpyadav.ece@mnit.ac.in

Abstract

This paper characterizes the Multi User Interference (MUI) as an impact of Transceiver Phase Noise (PHN) on Orthogonal Frequency Division Multiple Access (OFDMA) Uplink system performance for arbitrary subcarrier mapping, channel response and different powers and PHN levels for different users. In most of the previous publications Complex Gaussian distribution of Inter Carrier Interference (ICI) was assumed, however in this paper we derive a closed form expression for the signal-to-interference+ noise ratio (SINR) without such restriction and then verify it with simulator. This improved evaluation stringently specifies the plausible acceptable PHN characteristics for a certain OFDMA Uplink system and explains the serious under specification of Local Oscillator (LO) with Gaussian approximation.

Keywords: *CPE, FRO oscillator, ICI, MUI, OFDM/A, Phase Noise*

1. Introduction

Spurt demand of high data rate and high spectral efficiency led to a significant interest worldwide to operate close to Shanon Capacity Bounds. Orthogonal Frequency Division Multiplexing/ Multiple Access (OFDM/A) technique, at the heart of IMT Advanced, the standard for 4G, enables trivial one-tap equalization by Cyclic Prefix (CP) insertion. Moreover, the use of Discrete Fourier Transform (DFT) and its extremely efficient and well established Fast Fourier Transform (FFT) algorithm for implementation has made OFDM/A amenable in term of cost even, with great potential for providing high spectral efficiency due to its integrated space-frequency and multi-user diversity. The immediate consequences of operating at high data rates and high spectral efficiency are receiver non idealities, such as Phase Noise (PHN), Carrier Frequency Offset (CFO) and IQ (In and Quadrature Phase) imbalance effects, which were neglected previously, now become significant and need to be addressed. While CFO and IQ imbalance are deterministic, PHN on the other hand is random perturbations in the phase of the carrier signal generated by the transceiver oscillators. Further, PHN severely limits the performance of systems that employs dense constellations and degradation gets more pronounced in high carrier frequency systems.

In OFDM, in addition to the rotational effect called Common Phase Error (CPE), PHN also causes leakage of DFT, which subsequently produces ICI, serious ‘in-band’ effect of PHN, which destroys the orthogonality of the subcarriers by spreading their energies on top of each other [1-4]. The ‘out-of-band’ effect comes into play in the multiple access scheme of the OFDM (OFDMA), causing MUI. This interference is induced by the spectral spread of the energy of each user’s subcarriers on the top of other users’ subcarriers. The spread is more severe [5], when there are unequal power levels as well unequal transmitter PHN 3-dB bandwidths (PHN 3-dB BW) for different users due to

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[*] Corresponding Author

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different path loss effects and different oscillator non idealities respectively, in an uplink scenario.

ICI, which is a dominating factor over CPE, because of larger pass band cut off frequencies of low pass filter in OFDMA uplink scenario, is assumed to be Complex Gaussian distributed in majority of the literature available [1-4, 6-8]. In contrast for ‘Slow’ PHN model, where PHN does not change within one symbol, ICI is limit distributed with thicker tails in all practical systems even with large number of subcarriers [9-11]. One more important factor in OFDMA system, which was considered marginally in previous analytical methods [12-13], is MUI, which cannot be taken same as ICI in OFDM system. These two significant adaptations have been investigated in this work for accurate characterization of signal to interference+ noise ratio (SINR).

In this paper, after introducing a PHN model, a unified PHN corrupted OFDMA uplink signal model, which can characterize any subcarrier assignment (Contiguous and Interleave) scheme, is derived where each OFDMA user suffers from the transmitter PHN, which is more significant in OFDMA and receiver PHN as well. This is followed by characterization of SINR in terms of MUI, which is further analysed and simulated for PHN effects.

2. Phase Noise Modeling

Phase Noise (PHN) is the random fluctuations in phase of the sinusoidal waveform used for frequency up/down conversion of baseband signals to/from RF (Radio Frequency). This occurs due to the inherent imperfections of oscillators used for this purpose and so the output of a practical generator is noisy and can be written as:

$$\mathrm{s}(\mathrm{t}) = [\mathrm{A} + \mathrm{a}(\mathrm{t})]\sin[\mathrm{wt} + \varnothing(\mathrm{t})] \tag{1}$$

where A and w are amplitude and angular frequency respectively and $\mathrm{a}(\mathrm{t})$ is amplitude fluctuation which can be kept in limit by using an automatic gain controller. $\varnothing(\mathrm{t})$, the phase fluctuation (Time varying PHN), is very difficult to mitigate and can have major impact on system performance. Further note that in this work our focus is on oscillator phase synchronization and time synchronization is assumed to be perfect. In the present work we have considered Free Running Oscillator (FRO) model, with White Noise sources only so PHN ($\varnothing(n)$) can be modelled as a discrete-time Wiener process for which [14-15]:

$$\mathrm{E}\left[\varnothing(\mathrm{n})\right] = 0 \tag{2}$$

and

$$\mathrm{E}\left[(\varnothing(\mathrm{n}+\Delta\mathrm{n}) - \varnothing(\mathrm{n}))^2\right] = 4\pi\beta\mathrm{T}\left|\Delta\mathrm{n}\right| / \mathrm{N} \tag{3}$$

where β denotes one sided 3-dB BW of the Lorentzian power density spectrum, T is symbol duration, N is number of subcarriers and T/N is sampling interval. If $S_X(f)$ is the PSD (Power Spectral density) of the total oscillatory signal around the first harmonic, $S_\varnothing(f)$ is the PSD of PHN or excess phase $\varnothing(\mathrm{t})$ and $L(f)$ is the SSB (Single Side Band) PHN spectrum then:

$$L(f) = \frac{S_X(f_c + ?f}{P_s} \text{겏} S_\varnothing(f) \text{징} for \text{ 겂겏} f \le ?f_c \tag{4}$$

where f and f_c are offset and oscillation frequencies respectively and P_s is the total signal power around centre frequency. The Lorentzian spectrum is squared magnitude of a first order low pass filter transfer function and $S_{\varnothing}(f)$ is given by:

$$S_{\varnothing}(f) = \frac{2/\pi\beta}{1 + f^2/\beta^2} . \quad (5)$$

3. OFDMA Uplink Modelling

In this section we consider the uplink of an OFDMA system consisting of N $(n = 0,1,2.....N-1)$ subcarriers and K $(k = 1,2,3......K)$ users with the subcarrier spacing $\Delta f = \frac{B}{N}$ and sampling interval T/N where B is system bandwidth. In addition, u represents the index set of use full subcarriers with size U , that is among N subcarriers, the k^{th} user is assigned to a subset of U_k subcarriers with index set: $u_k = \{u^k{}_1 u^k{}_2 ......u^k{}_{Uk}\}$, either contiguous or interleaved where $(.)^k$ denotes the k^{th} user. If x_m^k is the m^{th} frequency domain symbols sent by the k^{th} user, then p^{th} entry of it, say $X_{m,p}^k$ is nonzero if $p \in u_k$. Thereupon discrete time baseband signal of the k^{th} user using IFFT (Inverse FFT) can be represented as:

$$s_m^k(n) = \frac{1}{N} \sum_{p \in u_k} X_{m,p}^k e^{j2\pi \frac{pn}{N}} \quad 0 \le n \le N-1. \quad (6)$$

Before transmitting over the channel this signal is preceded with CP of length Ng samples and duration T_{cp} such that it is longer than the channel impulse response. This implies that there is no ISI (Inter Symbol Interference) in between the windows of N samples (the effect of multipath is still experienced within each symbol), and that the whole processing can be done in a symbol to symbol manner. For this reason, OFDMA symbol index m is dropped hereafter. After this the signal is transformed back to the serial form and is up converted to RF with noisy transmitter oscillator and finally is sent over the channel. Let the discrete time composite channel impulse response with order L_k between the k^{th} user and the uplink receiver be denoted by $h^k(l)$ and the channel frequency response on the p^{th} subcarrier of k^{th} user's channel be denoted by H_p^k , then H_p^k can be given as:

$$H_p^k = \sum_{l=0}^{L_k-1} h^k(l) e^{-j2\pi \frac{pl}{N}} . \quad (7)$$

Denoting the discrete time Transmitter PHN process, Receiver PHN process and AWGN (Additive White Gaussian Noise) impairment to the k^{th} user by $\varnothing_T^k(n)$, $\varnothing_R^k(n)$ and $w(n)$ respectively, the received OFDMA symbol after down conversion and CP removal can be written as:

$$r(n) = \sum_{k=1}^{K} [(s^k(n) e^{j\varnothing_T^k(n)}) \otimes h^k(n)] e^{j\varnothing_R^k(n)} + w(n) . \quad (8)$$

It can be observed that equation (8) holds only approximately, because transmitter PHN affects the samples of the CP differently than the corresponding samples in the actual OFDMA signal part. After taking the FFT of $r(n)$, the frequency domain received symbol on the p^{th} subcarrier is:

$$R_p = \underbrace{\theta^k(0)}_{\text{CPE}} H_p^k X_p^k + \underbrace{\sum_{i=1}^{K} \sum_{\substack{q \in u_i \\ q \neq p}} \theta^i(p-q) H_q^i X_q^i}_{\text{ICI}} \text{?} + \underbrace{W_p}_{\text{AWGN}} . \tag{9}$$

As H is a circulant matrix, the transmitter PHN can be effectively mapped as receiver PHN by writing:

$$\varnothing_T^k(n) + \varnothing_R^k(n) = \varnothing_{?}^k(n) . \tag{10}$$

Thus, in equation (9), W_p is the AWGN noise in frequency domain and:

$$\theta^k(q) = \frac{1}{N} \sum_{n=0}^{N-1} e^{j \varnothing^k(n)} e^{-j\frac{2\pi nq}{N}} . \tag{11}$$

From equation (9), we find the effect of PHN in multiuser OFDM to be different from that of single user OFDM. First, the CPE term ($\theta^k(0)$) varies according to the index k, means that each user suffers from different CPE and need to be estimated and mitigated separately for each user. Secondly, the summative term, called ICI, includes the user's 'in-band' ICI (Self Interference (SI)) and ICI caused by MUI. While including the frequency domain dummy symbols transmitted by each active user in equation (9) a unified frequency domain signal model can be given by:

$$R_p = \sum_{k=1}^{K} \sum_{q=0}^{N-1} \theta^k(p-q) H_q^k X_q^k + W_p . \tag{12}$$

It can be noted that splitting of summative (ICI) term in equation (9) is important for our analysis purpose, as MUI takes in to account the significance of the power level of users as well the transmitter PHN 3-dB BW as these two will be significantly different for each user, precisely in case of OFDMA uplink. So the signal for k^{th} user, on p^{th} subcarrier is given as:

$$R_p = \underbrace{\theta^k(0)}_{\text{CPE}} H_p^k X_p^k + \text{?} \underbrace{\sum_{\substack{q \in u_k \\ q \neq p}} \theta^k(p-q) H_q^k X_q^k}_{\text{ICI (SI)}} + \underbrace{\sum_{\substack{i=1 \\ i \neq k}}^{K} \sum_{\substack{q \in u_i \\ q \neq p}} \theta^i(p-q) H_q^i X_q^i}_{\text{ICI (MUI)}} + \underbrace{W_p}_{\text{AWGN}} . \tag{13}$$

First to characterize the PHN strength in OFDMA transmission, we adopt a parameter widely used in literature [6-13], which is the relative PHN Bandwidth $\Delta_{\text{PN}} = \frac{\text{PHN? - dB BW}}{\Delta\text{f}\left(\text{subcarrier spacing}\right)}$. To incorporate the desired advantages of OFDM transmission over single carrier transmission along with 'slow' PHN model, one need to keep Δ_{PN} as small as possible and this makes the assumption of Complex Gaussian distribution of the ICI false even with higher number of subcarriers. Secondly a higher $3-\text{dB BW}$ of the PHN process and so the higher value of power level also can lead to more energy in the MUI factor of ICI terms. Considering these two facts and the OFDMA uplink scenario, not all the $K-1$ users will produce the MUI for k^{th} user but only those who will satisfy the following inequality will be the disruptive users for k^{th} user:

$$\sum_{a=1}^{N-1} E\left[\left|\theta^k(a)\right|^2\right] \text{?} \sum_{a=1}^{N-1} E\left[\left|\theta^j(a)\right|^2\right] \qquad \textit{for } j = 1 \textit{ to } K \textit{ and } j \neq k . \tag{14}$$

Now we define a subset of users for the k^{th} user, I_k, $\forall j \in I_k$ with size I_k.

Since the PSD of PHN tapers off rapidly beyond the loop bandwidth, most of the energy in a PHN sequence is contained in the frequency components corresponding to the first few orders. Hence, the largest contribution to interference on a particular sub-carrier is likely to come from users occupying adjacent sub-carriers. As a result, disruptive users who are occupying sub-carriers adjacent to the k^{th} user are likely to be most disruptive users. So the equation (13) can be modified while using equation (14) as:

$$R_p = \underbrace{\theta^k(0)H_p^kX_p^k}_{\text{CPE}} + \underbrace{\sum_{\substack{q\in \mathrm{u_k} \\ q\neq p}} \theta^k(p-q)H_q^kX_q^k}_{\text{ICI (SI)}} + \underbrace{\sum_{i\in I_k}\sum_{\substack{q\in \mathrm{u_i} \\ q\neq p}} \theta^i(p-q)H_q^iX_q^i}_{\text{ICI (MUI)}} + \underbrace{W_p}_{\text{AWGN}}. \tag{15}$$

4. Characterization of SINR due to Phase Noise

In this section we derive the signal-to-interference+ noise ratio (SINR) for OFDMA uplink case while acquiescing equation (14) which was proposed in the last section. Stemming from equation (12), (15) and [7, 16], SINR of p^{th} subcarrier is given by (using modulo $N-1$ indexing):

$$SINR_p = \sum_{k=1}^{K} \frac{E\left[\left|X_p^kH_p^k\theta^k(0)\right|^2\right]}{E\left[\left|W_p + \sum_{q=1}^{N-1} X_{p-q}^kH_{p-q}^k\theta^k(q) + \sum_{i\in Ik}\sum_{q=1}^{N-1} X_{p-q}^iH_{p-q}^i\theta^i(q)\right|^2\right]}. \tag{16}$$

With reasonable assumptions [7] that, H_p^k, X_p^k, W_p^k and $\theta^k(p)$ are mutually independent and stationary, and that $\forall p, \forall k$ X_p^k are mutually independent random variables with zero mean and variance σ^{2k}_p, we can write $\sigma^{2k}_p = E[|X_p^k|^2]$ and $\sigma_w^2 = E\left[\left|W_p^k\right|^2\right]$ so:

$$SINR_p = \sum_{k=1}^{K} \frac{\sigma^{2k}_p \sigma_H{}^{2k}_p E\left[\left|\theta^k(0)\right|^2\right]}{\sigma_w^2 + \sum_{q=1}^{N-1}\sigma^{2k}_{p-q}\sigma_H{}^{2k}_{p-q}E\left[\left|\theta^k(q)\right|^2\right] + \sum_{i\in Ik}\sum_{q=1}^{N-1}\sigma^{2i}_{p-q}\sigma_H{}^{2i}_{p-q}E\left[\left|\theta^i(q)\right|^2\right]}. \tag{17}$$

By using derivation for power of k^{th} DFT component of PHN complex exponential [13, 17], $SINR_p$ is given in equation (18) as its final form to analyse:

$$SINR_p = \sum_{k=1}^{K} \frac{\sigma^{2k}_p\sigma_H{}^{2k}_p\left[-\frac{1}{N}+\frac{2}{N^2}\sum_{n=0}^{N-1}(N-n)e^{-\frac{j2\pi\beta^kTn}{N}}\right]}{\sigma_w^2 + \sum_{q=1}^{N-1}\sigma^{2k}_{p-q}\sigma_H{}^{2k}_{p-q}\left[-\frac{1}{N}+\frac{2}{N^2}\sum_{n=0}^{N-1}(N-n)e^{-\frac{j2\pi\beta^kTn}{N}}\cos\left(\frac{2\pi pn}{N}\right)\right] + \sum_{i\in Ik}\sum_{q=1}^{N-1}\sigma^{2i}_{p-q}\sigma_H{}^{2i}_{p-q}\left[-\frac{1}{N}+\frac{2}{N^2}\sum_{n=0}^{N-1}(N-n)e^{-\frac{j2\pi\beta^iTn}{N}}\cos\left(\frac{2\pi pn}{N}\right)\right]} \tag{18}$$

This is the closed form solution to efficiently compute the effect of ICI (SI and MUI) on OFDMA signals in either contiguous or interleaved multiuser configuration.

5. Verification and Analysis of SINR

In this section all the formulation results are verified with respective simulation results in figures 1 to 5, where each simulation point is conducted using 10,000 OFDMA symbols in MATLAB. Simulation model is based on IEEE 802.11a like system with 64 subcarriers, out of which 52 are active in the 5GHz frequency band and transmission bandwidth is 20 MHz. Total bandwidth is divided in 4 sub channels with 13 subcarriers and each user utilizes one sub channel. The DC carrier as well the carriers at the spectral edges are not modulated and are virtual carriers. OFDMA Symbols are generated using 16-QAM (Quadrature Amplitude Modulation) and 64-point IFFT, and then prepended by CP of length 16 samples. Finally, transmitter PHN is modelled before transmitting over the AWGN channel. The combined received signal from all four users is then OFDMA demodulated with 64-point FFT after receiver PHN modelling followed by CP removal.

Each user is following the above described operation separately so that power and PHN 3-dB BW can differ specifically, if applicable.

In Figure 1, SINR of four OFDMA users with contiguous subcarrier mapping is depicted corresponding to their subcarrier index where user-2 have 5dB more power than the other users and all users as well receiver PHN 3-dB BW is 200 Hz. From the Figure 1, it can be observed that adjacent subcarriers to user-2 are experiencing very heavy SINR degradation because of 'out-of-band' (MUI) effect whereas the 'in-band' (SI) effect is relaxed because of high subcarriers' power.

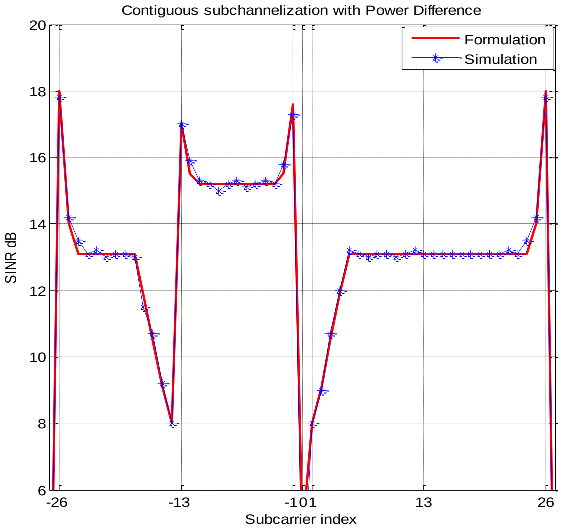

Figure 1. Subcarrier Wise Effect of MUI on SINR Performance for Contiguous Mapping with Power Difference while PHN 3-dB BW=200Hz

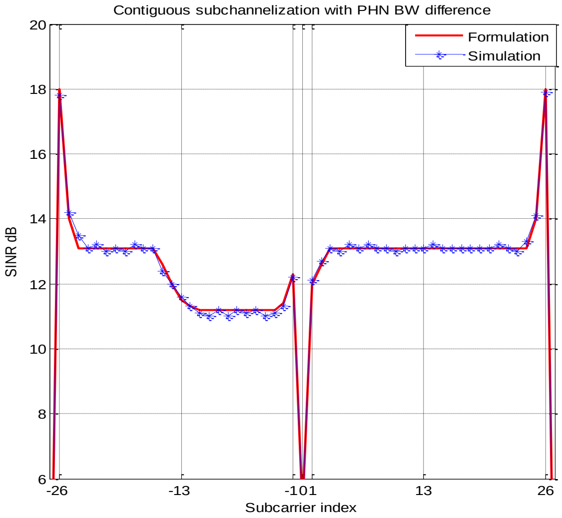

Figure 2. Subcarrier Wise Effect of MUI on SINR Performance for Contiguous Mapping with PHN 3-dB BW Difference while SNR=20dB

Similarly, as shown in Figure 2, when user-2 have 400 Hz PHN 3-dB BW, but all the other users as well receiver have 200 Hz PHN 3-dB BW, again the adjacent subcarriers are facing severe 'out-of-band (MUI)' effect but this time the 'in-band' effect is stronger as high PHN of user-2 is resulting higher SI than the other users with lesser PHN. By comparing the results of Figure 1 and Figure 2, it can be also observed that severity of MUI is more serious in case of Power difference.

In Figure 3, SINR of four OFDMA users with interleaved subcarrier mapping is depicted corresponding to their subcarrier index where user-2 have 400 Hz PHN 3-dB BW, but all the other users as well receiver have 200 Hz PHN 3 dB BW. Subcarriers of user-2 are marked with vertical dashed lines. In this case the average MUI to the adjacent users is around to contiguous mapping but the instantaneous effect is moderate as in case of interleaved mapping MUI impact is also distributed.

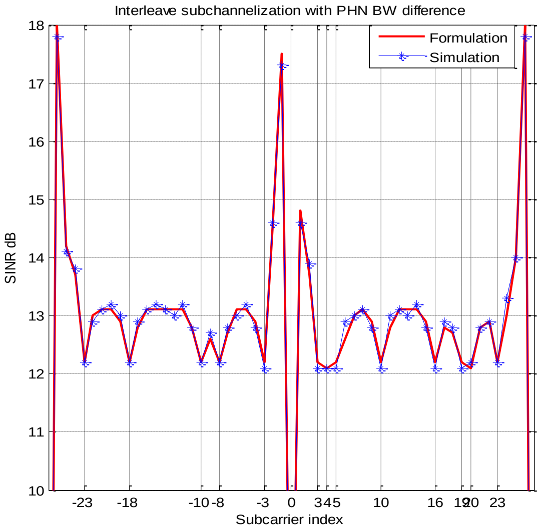

Figure 3. Subcarrier wise Effect of MUI on SINR Performance for Interleave Mapping with PHN 3-dB BW Difference while SNR=20dB

In Figure 4 average SINR for four users and average SINR of user-2 is simulated for contiguous mapping, where user 2's subcarriers have 5dB to 20 dB more power than the other users'subcarriers and all users as well receiver PHN 3-dB BW is 200 Hz. As user-2 gets power hike on the subcarriers, 'in-band (SI)' effect is limited, but power increment does not limit PHN effect when it reaches to high SNR region, as systems with high SNR are more sensitive to PHN. At the same time, since user-2 is producing more and more MUI, average SINR of all the users get degraded and this degradation is higher for higher SNR regions because of above stated reason.

Figure 5 shows the comparison of average SINR performance in case of Contiguous and Interleave mapping for four users, where all users as well receiver have 200 Hz PHN 3 dB BW excluding user -2, who has variation of PHN 3-dB BW from 200 to 800Hz, while all users' SNR is 20 dB . At 200 Hz the values of SINR coincides but as it is increased, Interleave mapping clearly shows the lower SINR performance than Contiguous mapping as in case of interleave mapping MUI is evenly distributed around the OFDMA symbol. As we increase the PHN 3-dB BW difference, degradation in SINR performance shows that with high PHN level, MUI is catastrophic.

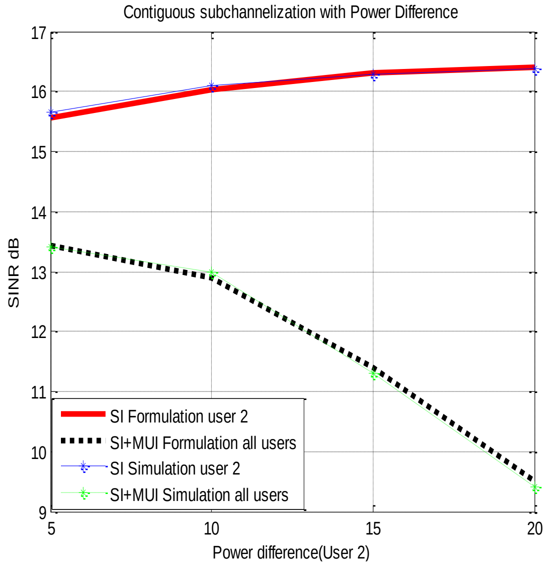

Figure 4. Effect of SI and MUI on Average SINR Performance for Contiguous Mapping with Power Difference while PHN 3-dB BW=200Hz

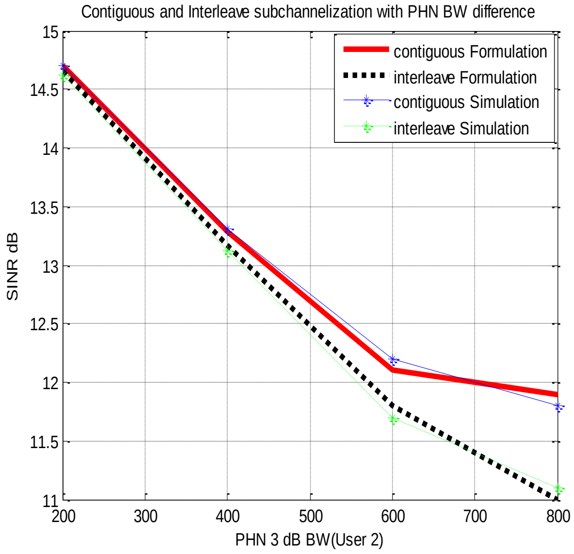

Figure 5. Comparison of Average SINR Performance for Contiguous and Interleave Mapping with PHN 3-dB BW Difference while SNR=20dB

6. Conclusion

Designing an OFDM/OFDMA-based communication system demands an accurate prediction of the tolerable PHN which can allow the system and RF engineers to relax the specifications. The transceiver PHN heavily degrades the performance of an OFDMA system as it creates MUI also. Accompanied with power and PHN level differences between the users at the transmitter, the PHN induced spread causes further performance degradation for users with low signal powers. In this paper an improved evaluation of OFDMA system performance is studied in terms of SINR, which is derived in this paper to extend the state of art results and to have an insight of PHN effect on the actual system as a function of power level and PHN level differences in case of both type of mappings. The simulation verifies the analysis results and also proves that non Gaussian distributed

ICI produces serious degradation in the system performance even with small PHN 3-dB BWs. This efficient analysis will allow the design of oscillators to meet the necessary PHN requirements and hence ensures satisfactory performance of the overall system.

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Authors

Kamayani Shrivastav received her B.E. degree from Rajasthan University, India, from the Department of Electronics and Communication Engineering in 2002 and completed her M.Tech dissertation work in the area of Turbo Coding for Wireless Communication systems. She worked as Assistant Professor for 12 years and now is doing research work as a Ph.D. scholar at MNIT, Jaipur, India. Her research area comprises, Error Control Codes, MIMO-OFDM/A, Mobile and Wireless Communication Systems, and Mobile Ad-hoc and Sensor Network.

Prof. R. P. Yadav completed his M.Tech dissertation work in the area of device characterization and Ph.D. work under the project RESPOND of ISRO Bangalore, India, in Communication Engineering. He was instrumental in formulating Ph.D. Ordinances and starting research work in RTU Kota, India, as Vice Chancellor. He is part of several committees of institute, various Universities, state government and National bodies, (Chairman, NWRC AICTE Chandigarh, India), formed to address various academic, collaborative research and policies of technical education. His research area comprises, Error Control Codes, MIMO-OFDM, RF and Antenna Systems, Mobile and Wireless Communication Systems, Optical Switching and Materials, Mobile Ad-hoc and Sensor Network, Device Characterization and MEMS.