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Case Study Article

OFDM SYSTEMS BASED ON INTER CARRIER INTERFERENCE WITH ASB

R.RAVI[1], DR. N. SUTHANTHIRA VANITHA[2]

[1]Research Scholar, Anna University, Chennai, [2]Professor & Head, Department of EEE, KIOT, Salem, India. Email: ravi22nirai@gmail.com, varmans03@yahoomail.com

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ABSTRACT

Orthogonal frequency division multiplexing based wireless systems are spectrally efficient and it is being increasingly used in high data rate wireless communication systems, but they are vulnerable to inter carrier interference (ICI). The signal strength varies due to different individual path loss and also due to different amount of Doppler spread because of their independent velocities. Therefore, the ICI among users will vary over a wide range. Most approaches to combat ICI are towards using synchronization and interference cancellation. They are usually very complex and sometimes there is loss in bandwidth efficiency. In all existing systems sub carrier bandwidth is kept constant. In this paper we use adaptive sub carrier bandwidth (ASB) along with adaptive bit loading to mitigate ICI in such conditions, which will keep receiver design very simple and it keeps maximum throughput and minimum BER in each situation. Results show that ASB can provide higher throughput than fixed sub carrier bandwidth.

Keywords: OFDM, ICI, frequency offset, Adaptive Subcarrier bandwidth, Doppler spread.

INTRODUCTION

Orthogonal frequency division multiplexing (OFDM) is expected to be one of the basic physical layer technologies for future generation wireless systems. With its long symbol duration it has strong capability to withstand multi-path fading. Using orthogonal sub carriers it can support for high data rate communication systems.

The fundamental principle of the OFDM is to decompose the high rate data stream (bandwidth=**W**) into **N** lower rate data streams and then to transmit them simultaneously over a large number of sub carriers. A sufficiently high value of **N** makes the individual bandwidth (**W/N**) of sub carriers narrower than the coherence bandwidth (**Bc**) of the channel. The choice of individual sub carrier is such that they are orthogonal to each other, which allows for the overlapping of the sub carriers because the orthogonality ensures the separation of sub carriers at the receiver end [1]. Loss of orthogonality between the sub carriers causes the Inter Carrier Interference (ICI).Though it can support high spectral efficiency, yet it is highly vulnerable to frequency synchronization errors. Such errors come from residual carrier frequency offset, sampling frequency offset, phase noise and Doppler frequency spread. Since carrier synchronization algorithms are designed to track only one frequency offset, it becomes difficult to eliminate the frequency spread due to Doppler. These impairments cause loss in orthogonality between the sub carriers and give rise to ICI, which severely limits the performance of OFDM systems [2].

ICI is inversely proportional to sub carrier bandwidth [2]. Previous papers use synchronization and interference cancellation methods to combat ICI. But these processes are very complex and sometimes it causes loss in bandwidth efficiency. Another consideration is different users will have different BER requirement as per the service. These algorithms do not address these issues. In all existing systems sub carrier bandwidth is kept constant. The proposed flexible OFDM system, which can adaptively select the sub carrier bandwidth and bit loading, based on Doppler condition, signal strength and bit error rate requirement is not found in the available literature. The focus of this work is to investigate the performance of such an OFDM system which uses adaptive sub carrier bandwidth [2].

The organization of this article is as follows: Impairment issues in OFDM systems causing ICI is described in section **II**. Section **III** contains analytical model of the system. Section **IV** contains an algorithm to implement ASB. Section **V** contains results and discussion and Section **VI** contains conclusion.

Impairment issues in OFDM Systems causing ICI

Sampling clock Frequency offset

Frequency offset in OFDM system is introduced by the receiver analog- to -digital (A/D) sampling clock , which will seldom have the exact period matching the transmit sampling clock , causing the receiver sampling instants slowly to drift relative to the transmitter. The sampling error manifests in two ways: First, a slow variation sampling time causes loss of orthogonality between the sub carriers and second subsequent loss in SNR due to ICI. Let us define the normalized sampling error as [1]

$$\mathbf{t_0=\frac{T'-T}{T}} \qquad (1)$$

Where **T** and **T'** are transmit and receive sampling periods respectively.

The degradation can be expressed as SNR loss in dB by the following expression

$$\mathbf{D=10log_{10}[1+\frac{\Pi^2}{3}\frac{Es}{N_0}(k\,t_0)^2\,]} \qquad (2)$$

Where **k** is the sub carrier index and $\frac{Es}{N_0}$ is SNR. The effect of sampling offset on SNR degradation is shown in Fig.1. as the function of number of sub carriers. From Fig.1. it is obvious that as the number of sub carriers in OFDM symbol increases,degradation also increases.

Carrier frequency offset

The OFDM systems are more sensitive to frequency error than single carrier frequency systems. The frequency offset is produced at the receiver because of local oscillator instability and variability of operating conditions at transmitter and receiver. The effect of carrier frequency offset effect on SNR degradation which is given by [1]

$$\mathbf{SNRloss\ (dB)=\frac{10}{3\ln 10}(\Pi T\delta_{fc})^2\frac{Es}{N0}} \qquad (3)$$

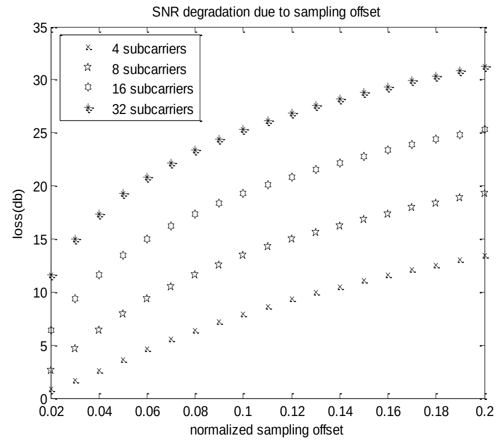

Fig.1: SNR degradation due to sampling offset

Where $\boldsymbol{\delta_{fc}}$ is frequency offset and it is the function of sub carrier spacing and **T** is the sampling period Fig.2. Shows total ICI loss due to loss in orthogonality .ICI loss increases with the increase in offset.

Timing offset

The symbol timing is very important to the receiver for correct demodulation and decoding of incoming data sequence. The timing synchronization is possible with the introduction of the training sequences in addition to the data symbols. The receiver may still not able to recover the complete timing reference of the transmitted symbol because of the channel impairments that are causing the timing offset between transmitter and the receiver. A timing offset give rise to the phase rotation of the sub carriers which causes loss which is given by [1]

$$\mathbf{ICI_{dB}= 10\ log_{10}[2(\tfrac{\tau}{T})^2]} \quad (4)$$

Where **τ** denotes timing offset between two consecutive symbols.

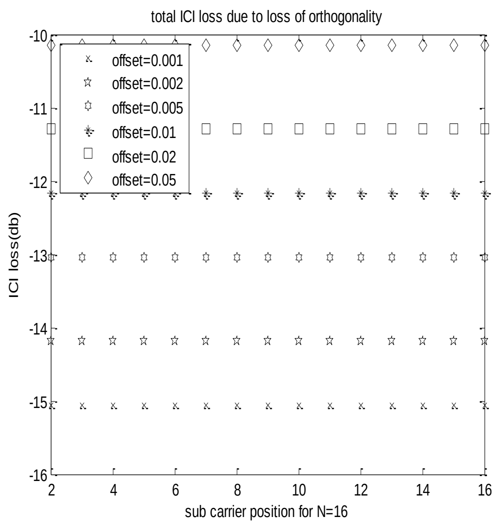

Fig.2: Total ICI loss due to loss of orthogonality

Carrier phase noise

The carrier phase impairment is induced due to the imperfection in the transmitter and the receiver oscillators. The phase rotation could be the result of either the timing error or the carrier phase offset for a frequency selective channel. The carrier phase noise is modelled as Wiener process $\boldsymbol{\Theta(t)}$ with $\mathbf{E[\{\Theta(t_0+t)-\Theta(t_0)\}^2]=4\Pi\beta|t|}$, $\mathbf{E\{\Theta(t)\}=0}$, where **β**(in Hz) denotes the single –sided line width of the Lorentzian power spectral density of the free running carrier generator. Degradation in SNR can be approximated by [1], [3]

$$\mathbf{D(dB)=\frac{11}{6\ln 10}\left(4\pi\ N\ \frac{\beta}{W}\right)\frac{Es}{N_0}} \quad (5)$$

Where **W** is the bandwidth and $\mathbf{\frac{Es}{N_0}}$ is the SNR of the symbol [1]. From Fig.3. We can conclude that the degradation increases with the increase in number of sub carriers.

Multipath issues

In mobile wireless communication, a receiver collects transmitted signals through various paths, some arriving directly, some from neighbouring objects because of reflection, and some even because of diffraction from nearby obstacles. The various paths arriving at the receiver may interfere with each other and cause distortion to information bearing signal. The Doppler shift is introduced because of the relative motion of between the transmitter and the receiver and can be expressed as [1], [6]

$$\mathbf{f_D= \frac{v\cos\theta}{\lambda}} \quad (6)$$

Where **V** is the relative velocity between transmitter and receiver, **λ** is wavelength of the carrier, **Θ** is the phase angle between the transmitter and receiver.

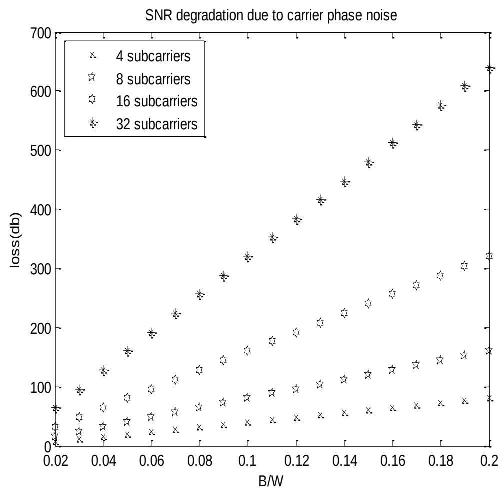

Fig.3: SNR degradation due to carrier phase noise

Effects of imperfect channel estimation:

Channel estimation is mandatory if coherent modulation is used. Imperfect channel estimation may cause SNR loss which may also cause loss of orthogonality between the sub carriers [9]. For example for the two-dimensional Wiener channel estimator, the estimation power is given by [9]

$$\boldsymbol{\sigma_H^2 = \frac{1}{G}\,\sigma_N^2} \quad (7)$$

Where **G** is the estimator gain factor, $\boldsymbol{\sigma_H^2}$ is estimated noise power and $\boldsymbol{\sigma_N^2}$ is the channel noise variance .So performance loss becomes

$$\Delta^{\gamma}\mathbf{=1+\frac{1}{G}} \quad (8)$$

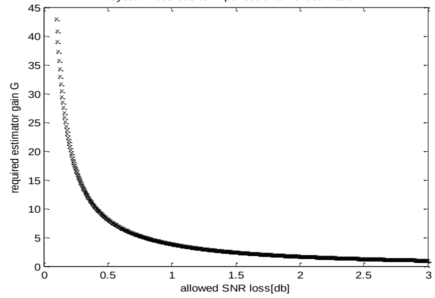

Fig.4: System loss due to imperfect channel estimation

Fig.4. displays the required estimator gain G versus the allowed system degradation. This result shows the importance of quality requirement on channel estimation. An estimator gain as high as ***G***=10 entails a system loss of 0.41 dB , where as an allowable loss of 0.1 dB would necessitate an extremely high gain of ***G***=43.

Analytical Model

The time domain signal of S^{th} transmitted symbol can be given as [2]

$$X_s(t)=\frac{1}{\sqrt{Tf}}\sum_{k=\frac{-Nf}{2}}^{\frac{Nf}{2}+1} x[s,k]\, e^{j2\Pi\frac{k}{Tf}(t-sTs-T_{gi})} \qquad (9)$$

Where **Tf** is the duration of OFDM symbol without Guard interval. **k** is the sub carrier index , **Nf** denotes number of sub carriers, **x[s,k]** denotes modulated data symbol on the sub carrier ,**Ts** is the symbol duration which is the sum of **Tf** and guard interval time period T_{gi}.

After passing through the channel the signal can be represented as [2]

$$r(t)=\int_0^{\tau_{max}} h(\tau)\, e^{j\,2\,\Pi\, f_{d\tau}(t-\tau)}\, x_{s(t-\tau)}\, d\tau + v(t) \qquad (10)$$

where $h(\tau)$ represents the channel impulse response,τ_{max} is its maximum tail ,**v(t)** is the noise component and $f_{d\tau}$ is the Doppler frequency for delay τ .With perfect timing synchronization , but residual carrier frequency offset δ_{f_c}(Hz) ,the received OFDM symbol is

$$r_s(t)=r(t)\, e^{(j2\Pi\delta_{f_c}t)} \qquad (11)$$

The signal portion without noise part is

$$\int_0^{\tau_{max}} h(\tau)X_S(t-\tau)e^{j\,2\,\Pi f_{d\tau}}\, e^{j\,2\Pi\delta_{fc}t} \qquad (12)$$

Since $h(\tau)$ $e^{-j2\Pi f_{d\tau}}$ cannot be distinguished from $h(\tau)$, we can represent $h(\tau)e^{j\,2\,\Pi f_{d\tau}}$ as $h(\tau)$ therefore,

$$r_s(t)=\int_0^{\tau_{max}} h(\tau)X_S(t-\tau)\, e^{j\,2\Pi(\delta_{fc+f_{d\tau}})t} \qquad (13)$$

Considering the channel coefficients remain static over a small period of time, which is less than coherence time, the term $(\delta_{fc+f_{d\tau}})$ is called as effective carrier offset [2] and represented as δf. The relative offset i.e. the ratio of effective offset to the sub carrier spacing can be represented as $\varepsilon \equiv \frac{\delta f}{\Delta f_{sc}}$. For the small values of $\frac{\delta f}{\Delta f_{sc}}$ the ICI power at the receiver on the sub carrier **k'** is [2]

$$\sigma^2_{ICI_{X[K']}}=\frac{1}{3}P_X P_{H[K']}\left(\Pi\,\frac{\delta f}{\Delta f_{sc}}\right)^2 \qquad (14)$$

$P_{H[K']}$ is the average power of channel coefficient and P_X average power per sub carrier.

Therefore Signal to Interference plus Noise ratio (SINR) is [2]

$$\gamma_{rx}[k']=\frac{P_{X[k']}P_{H[K']}\,\mathrm{sinc}\left(\left(\Pi\frac{\delta f}{\Delta f_{sc}}\right)^2\right)}{\frac{1}{3}P_X P_{H[K']}\left(\Pi\frac{\delta f}{\Delta f_{sc}}\right)^2+\sigma_{\omega^2}} \qquad (15)$$

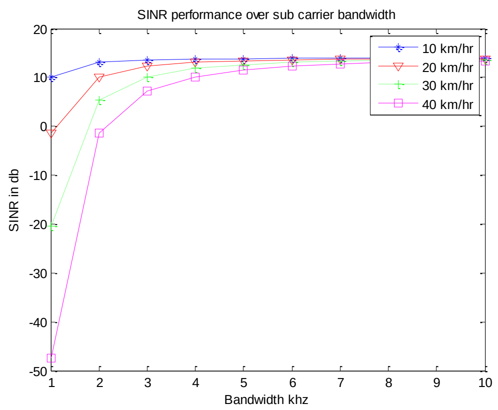

Fig.5: SINR vs. Sub Carrier Bandwidth at SNR=15 dB.

Adaptive Bandwidth For Sub Carriers

We propose an algorithm here, to dynamically Select the appropriate sub carrier bandwidth and bit load per sub carrier to maximize the throughput while satisfying a required BER is presented here. The sub carrier bandwidth can be chosen as [2]

$$\Delta f_{chosen} = \arg\max\,[Thpt\,(\Delta f_m)] \qquad (16)$$

Subject to

$$\Delta_{f_m} < B_c \text{ and} \qquad (17)$$

$$T_s < T_C \qquad (18)$$

Where B_c is coherence bandwidth, T_C is the coherence time, Δf_m is sub carrier bandwidth.

SINR can be computed by the below equation

$$\gamma_{rx}[k,\Delta f_m]=\frac{P_X P_{H[k]}\,\mathrm{sinc}\left(\left(\Pi\frac{\delta f}{\Delta f_{sc}}\right)^2\right)}{\frac{1}{2}P_X P_{H[k]}\left(\Pi\frac{\delta f}{\Delta f_{sc}}\right)^2+\sigma_{\omega^2}} \qquad (19)$$

where σ_{ω^2} is the noise variance of the sub carrier. The bit load estimate per sub carrier can be expressed as [4], [2]

$$b_L(K,\Delta f_m)=2\left\lfloor\frac{1}{2}\log_2\left(1-\frac{1.6}{\ln\left(\frac{b0\,req}{0.2}\right)}\right)\gamma_{rx}[k,\Delta f_m]\right\rfloor \qquad (20)$$

where ⌊.⌋ operator is the floor operation. In the above expression **b0 req** is the target BER which is to be satisfied.

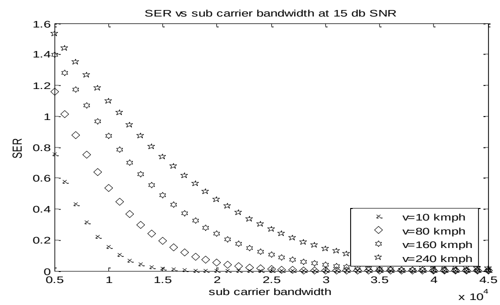

Fig.6: SER vs. Sub Carrier Bandwidth at SNR=15 dB

The BER associated with the chosen bit load is [2]

$$b_0(k,\Delta f_m)=0.2\,e^{\frac{-1.6\,\gamma_{rx}[k,\Delta f_m]}{2^{b_L(k,\Delta f_m)}-1}} \qquad (21)$$

The Symbol Error Rate (SER) for QAM modulation can be computed using [5], [8]

$$SER \leq 4Q\left(\sqrt{\frac{3\,\gamma_{rx}[k,\Delta f_m]}{2(M_0-1)}}\right) \qquad (22)$$

Where $Q(x)=\frac{1}{2}\,\mathrm{erfc}\left(\frac{x}{\sqrt{2}}\right)$, where erfc is the complementary error function and M_0 is the modulation order. For 64-QAM ,$M_0=64$, for 16-QAM $M_0=16$,etc . For computing throughput for each sub carrier [5]

$$b_L(K,\Delta f_m)(1-SER)\frac{T_u}{T_S} \qquad (23)$$

can be used, where $b_L(K,\Delta f_m)$ is the number of bits in the modulation used for the system.

The following steps are executed in sequence.

1) Select one sub carrier bandwidth from the available options.
2) Evaluate (19), i.e. SINR at each sub carrier for the selected sub carrier spacing.
3) Bit load per estimate is calculated using (20).
4) Calculate the BER for each sub carrier for the chosen bit loading using (21).
5) Calculate SER using the equation (22)
6) Use the above calculations and find estimated throughput using the equation (23).

7) Store the value of estimated throughput along with the value of sub carrier band width and associated bit loads per sub carrier.
8) Repeat all the above steps for all possible values of sub carrier bandwidth.
9) Execute (16) ,(17),(18) to find best sub carrier bandwidth.

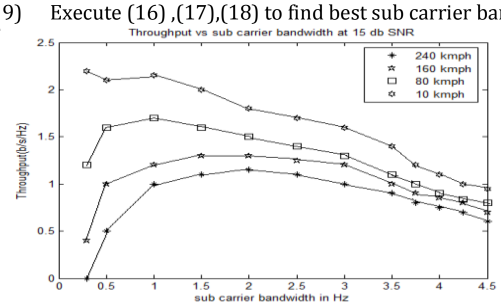

Fig.7: Throughput vs. Sub Carrier Bandwidth at SNR=15 dB

RESULTS AND DISCUSSION

For the simulation each coefficient is taken as Rayleigh distributed with Jakes' spectrum [7]. Exponential power delay profile is taken with rms delay spread of 2 micro seconds. Bandwidth of 5 MHz at carrier of 3.6 GHz is considered. The target BER is kept 0.01. Number of bits that can be loaded for sub carrier are 0,2,4,6,8 and 10 ,where 0 means no transmission.

The curves named as 2048, up to 256, are for fixed systems with as many sub carriers. The system with 2048 sub carrier has Δf_m=2.4 KHz. The system with 1024 sub carrier has Δf_m=4.88 KHz. The system with 512 sub carrier has Δf_m=9.77 KHz. The system with 256 sub carrier has Δf_m=19.531 KHz [2].

Fig.5. shows the plot of SINR vs. sub carrier bandwidth for different velocity conditions. Each curve is for a particular velocity. From the plot we can conclude that SINR improves with the increase in sub carrier bandwidth.Fig.6. Shows the plot between SER and sub carrier bandwidth at 15 dB SNR. From the plot we can conclude that OFDM SER decreases with the increase in sub carrier bandwidth. In Fig.6. Each curve is for a particular velocity.

Fig.7. shows the plot between Throughput and sub carrier bandwidth at SNR of 15dB. Throughput curves have been obtained by considering adaptive bit loading per sub carrier. This figure shows that throughput increases with the increase in sub carrier bandwidth and after some range of sub carrier bandwidth it starts decreasing. From this figure we are selecting the sub carrier bandwidth. The bandwidth for which throughput is maximum that is chosen as sub carrier bandwidth for the particular Doppler velocity.

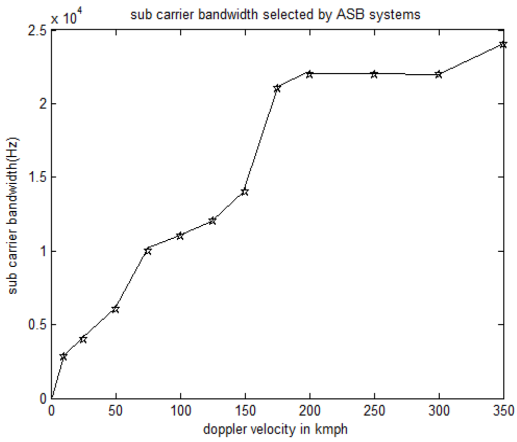

Fig.8: Sub Carrier Bandwidth selected by ASB systems.

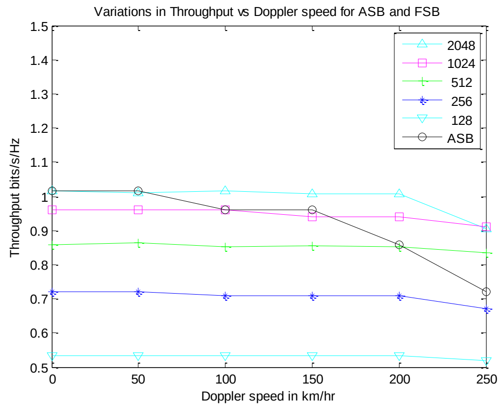

Fig.9: Throughput comparison of ASB vs. FSB OFDM systems, at SNR=15 dB

Fig.8. shows the sub carrier bandwidth selected by ASB systems. It shows that sub carrier bandwidth increases with the increase in Doppler velocity.Fig.9. shows the Throughput comparison of ASB vs. FSB OFDM systems, at SNR of 15 dB. The throughput is optimum for ASB than FSB for different Doppler velocities. ASB with ABL improves throughput by a significant amount.

Fig.10.shows the BER comparison of ASB vs. FSB OFDM systems for target BER of 0.01. Using adaptive bit loading (ABL) the BER is maintained below the target level for all the systems and velocities. Though the target BER is satisfied by both schemes (FSB and ASB) using ABL, it can be said that ABL is not sufficient for FSB OFDM system to be efficient for all Doppler conditions.

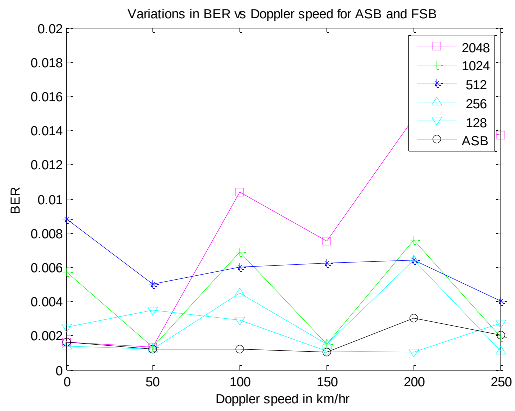

Fig.10: BER comparison of ASB vs. FSB OFDM systems when target BER=0.01.

CONCLUSION

It can be concluded that OFDM using ASB, presented in this work can improve the throughput performance of FSB systems by 10% to 30 % . The FSB system is optimum over a small range of velocities and but ASB system has optimum performance over all conditions. ASB also avoids complex compensation or interference cancellation mechanism at the receivers. In this paper the impairments such as Timing offset, Carrier Phase Noise, Channel Estimation Error, Synchronization Error along with the use of Forward Error Control Coding, Channel Information Feedback Delay are not considered. Now we are working on these impairments which also cause ICI.

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