A REVIEW ON CARRIER FREQUENCY OFFSET ESTIMATION IN OFDM SYSTEMS

[1]Ankita Yadav
Research Scholar, M. Tech.
Digital Communication, GGCT, Jabalpur

[2]Akanksha Dixit
Assistant Professor,
Dept. of ECE, GGCT, Jabalpur

Abstract*-This paper is a review of the various techniques for carrier frequency offset (CFO) estimation in orthogonal frequency division multiplexing (OFDM). The performance of OFDM system is much sensitive to CFO, which causes inter-carrier interference (ICI). In cyclic prefix (CP) based estimation, the CFO can be estimated from the phase angle of the product of CP & corresponding end part of the OFDM symbol. In CFO estimation using training symbol, the CFO estimation range can be increased by reducing the distance between two blocks of samples for correlation. This was made possible by using training symbol that are repetitive with shorter period. Bit Error Rate vs Signal to Noise Ratio & mean square error (MSE) are the some characterization parameters of the system to observe the effects of frequency offset synchronization.

Keywords*- Orthogonal Frequency Division Multiplexing (OFDM), Carrier Frequency Offset (CFO), Inter-Carrier Interference (ICI).

1. INTRODUCTION

OFDM system is widely used in multi-carrier modulation schemes. Multicarrier modulations are increasingly used in various telecommunication systems such as in Digital Audio Broadcasting (DAB), Digital Video Broadcasting Terrestrial (DVBT), digital broadband communications, Long Term Evolution (LTE), WiMAX. Despite of advantages of Multicarrier Modulation, it presents drawbacks such as sensitivity to Carrier Frequency Offset (CFO), Symbol Timing Offset (STO) and high Peak to Average Power Ratio (PAPR). This paper deals with estimating CFO. Various researches had been proposed to estimate this CFO [4]. These Techniques use FT in OFDM block diagram. Many of them give good results in term of MSE.OFDM is very sensitive to time and frequency synchronization. The synchronization problem consists of two major parts: carrier frequency offset (CFO) and symbol time offset (STO). This is due to Doppler shift and a mismatch between the local oscillator at the transmitter and receiver. In STO, time domain δ sample and phase shift offset is affected in the frequency domain. Frequency synchronization error destroys the orthogonality among the sub carriers which causes inter carrier interference (ICI) [2]. Therefore the CFO synchronization is essential to OFDM system. The CFO estimation has been extensively investigated for single input single output (SISO) and for multiple inputs multiple outputs (MIMO) OFDM based system. The normalized CFO can be divided into two parts which are integral CFO (IFO) ξi and fractional CFO (FFO) ξf. IFO produce a cyclic shift by ξi in receiver side to corresponding sub carrier it does not destroy orthogonality among the sub carrier frequency component and FFO destroys the orthogonality between the sub carriers. For CFO estimation in time domain, cyclic prefix (CP) and training sequence are used. CP based estimation has analyzed assuming negligible channel effect. CFO can be found from the phase angle of the product of CP and the corresponding part of an OFDM symbol, the average has taken over the CP intervals and in training sequence estimation using training symbol that is repetitive with some shorter period.

The orthogonality of the OFDM relies on the condition that transmitter and receiver operate with exactly the same frequency reference. If this is not the case, the perfect orthogonality of the subcarrier will be lost, which can result to subcarrier leakage, this phenomenon is also known as the Inter Carrier Interference (ICI) [1]. In another word, the OFDM systems are sensitive to the frequency synchronization errors in form of CFO. CFO can lead to the Inter Carrier Interference (ICI); therefore CFO plays a key role in Frequency synchronization. Basically for getting a good performance of OFDM, the CFO should be estimated and compensated. Lack of the synchronization of the local oscillator signal (L.OSC); for down conversion in the receiver with the carrier signal contained in the received signal causes Carrier Frequency Offset (CFO) which can create the following factors:

(i) Frequency mismatched in the transmitter and the receiver oscillator
(ii) Inter Carrier Interference (ICI)
(iii) Doppler Effect (DE).

P. Muneer et-al **[1]**, addressed the joint estimation of doubly elective channels (DSCs) and carrier frequency offsets (CFOs) in multiple input multiple output orthogonal frequency division multiple access uplink with highly mobile users. Since the channel coefficients are rapidly varying over time and the base station has to perform the estimation task from the received composite signal, the exact solution to this joint estimation problem requires multidimensional search which is computationally intensive. They proposed an iterative technique for the joint estimation of DSCs and CFOs based on space alternating generalized expectation maximization algorithm which will decompose the multidimensional optimization to many one dimensional searches. The proposed method works even in the presence of residual timing offsets and it does not require the knowledge of channel statistics at the receiver. Convergence properties of the proposed algorithm in terms of rate matrix is studied and analytically proved that the proposed joint estimation algorithm converges.

Ann-Chen Chang [2], presents computationally efficient subspace-based estimators to estimate carrier frequency offset (CFO) for interleaved orthogonal frequency division multiple access (OFDMA) uplink systems. Conventional subspace-based estimators rely on Eigen value decomposition (EVD) of sample correlation matrix to compute signal subspace or noise subspace. For interleaved OFDMA with large sub-channel, conventional subspace-based CFO estimators inevitably lead to intensive computational complexity due to calculating sample correlation matrix and it’s EVD. To circumvent this problem, in conjugation with center-symmetric trimmed correlation matrix and Nystrom method, the required signal subspace or orthogonal projection matrix only needs to calculate two submatrices of center-symmetric trimmed correlation matrix. Therefore, the proposed signal subspace-based and noise subspace-based estimators not only can estimate CFO, but also save computational cost, especially in high SNR and large sub-channel scenarios. Computer simulation results are also provided for illustrating the effectiveness of the presented blind CFO estimators under single OFDMA data block.

Roee Shaked et-al **[3]**, studied carrier frequency offset estimation for linear channels with periodic characteristics and has designed a maximum likelihood estimator (MLE), analytically characterize its asymptotic performance, and provide guidelines for its low-complexity implementation. They compare the strengths and weaknesses of the new estimator to those of an ad-hoc extended estimator obtained by adapting an MLE, originally designed for time-invariant channels, to periodically time-varying channels via a time partitioning approach. We numerically evaluate the performance of the new estimator and of the adhoc estimator, and illustrate the gain of rigorously accounting for the periodic characteristics of the channel, as opposed to the currently prevailing ad-hoc approach.

Dajin Wang et-al**[4]**, discussed the problem of carrier frequency offset (CFO) estimation for orthogonal frequency division multiplexing (OFDM) systems. An approximated method for CFO estimation is derived. They show that the introduction of CFO can be taken as the result of passing through a frequency domain filter, whose coefficients are functions of CFO. To estimate the CFO, we construct an estimator based on the filter coefficients. In this way, the CFO estimation problem is converted to filter coefficients estimation. They develop a fast algorithm with lower computational complexity. Results show that this method is effective for channel with large Doppler spread.

Tzu C. Lin et-al**[5]**, proposed a new blind CFO estimation for OFDM systems based on the so-called remodulated received vectors. The estimation of carrier frequency offset (CFO) is an important issue in the study of the orthogonal frequency division multiplexing (OFDM) systems. In the past, many CFO estimation methods have been proposed. The CFO estimate is given by a closed form formula. The proposed method has very low complexity and its performance is robust to different modulation symbols and the presence of virtual carriers.

Yufei Jiang et-al**[6]**, gave a semi-blind multiple-input multiple Output (MIMO) orthogonal frequency division multiplexing (OFDM) system, with a precoding aided carrier frequency offset (CFO) estimation approach, and an independent component analysis (ICA) based equalization structure. A number of reference data sequences are carefully designed offline and are superimposed to source data via a non-redundant linear precoding process, which can kill two birds with one stone, without introducing any extra total transmit power and spectral overhead. First, the reference data sequences are selected from a pool of carefully designed orthogonal sequences. The CFO estimation is to minimize the sum cross-correlation between the CFO compensated signals and the rest orthogonal sequences in the pool. Second, the same reference data enable elimination of the permutation and quadrant ambiguity in the ICA equalized signals by maximizing the cross-correlation between the ICA equalized signals and the reference data. Simulation results show that, without extra bandwidth and power needed, the proposed semi-blind system achieves a bit error rate (BER) performance close to the ideal case with perfect channel state information (CSI) and no CFO. Also, the precoding aided CFO estimation outperforms the constant amplitude zero autocorrelation (CAZAC) sequences based CFO estimation approach, with no spectral overhead.

P. Malarvezhi et-al**[7]**, presented a modified preamble structure based approach for CFO and phase noise compensation in an OFDM systems which mitigate the effect of inter carrier interference and its equivalent energy loss.

The Systems using Orthogonal Frequency Division Multiplexing (OFDM) suffer with carrier frequency offset (CFO)and phase noise which results in inter carrier interference (ICI)due to which there will be large performance degradation. The impairments like CFO and phase noise are caused due to mismatch of carrier frequency at the transmitter to local oscillator frequency at the receiver, multipath and Doppler shift. Theoretical analysis and simulation results substantiate the importance and advantages of proposed CFO and phase noise compensation approach. This proposed method provides a considerable signal to noise ratio gain on bit error rate performance

S. Kumarapandian et-al**[8]**, analyzed the non-cooperative Orthogonal Frequency Division Multiplexing (OFDM) and Cooperative-OFDM communication system by comparing their performances. Carrier frequency offset (CFO) mitigation is critical for OFDM based cooperative transmissions because even small CFO per transmitter may lead to severe performance loss, especially when the number of cooperative transmitters is large. They showed that cyclic prefix (CP) can be exploited to mitigate or even remove completely the CFO. The mitigation performance increases along with the CP length. In particular, long CP with length proportional to N*I, where N is the Fast Fourier Transform (FFT) block length and I is the number of cooperative transmitters, can guarantee a complete CFO removal. While this comes with a reduction in bandwidth efficiency, the long CP in the proposed scheme is exploited to enhance transmission power efficiency in a way similar to spread-spectrum systems, and thus is different from conventional CP that degrades both bandwidth and power efficiency. Authors showed that how performance of mitigation algorithm vary with cyclic prefix length and performance evaluation in case of error up in the estimation of carrier frequency offset (CFO).Comparing the performance of this mitigation algorithm with Orthogonal Frequency Division Multiple Access (OFDMA) mitigation algorithm for different carrier frequency offset values.

2. EFFECTS OF FREQUENCY OFFSET ON OFDM SIGNALS

When CFO happens, it causes the receiver signal to be shifted in frequency (δf); this is illustrated in the figure 1.If the frequency error is an integer multiple I of subcarrier spacing δf, then the received frequency domain subcarriers are shifted by δf x I .

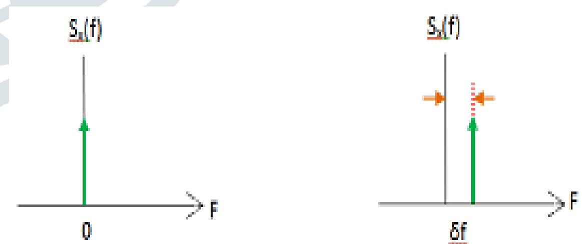

Figure 1: Frequency Offset

On the other hand, as we know the subcarriers (SCs) will sample at their peak, and this can only occur when there is no frequency offset, however if there is any frequency offset, the sampling will be done at the offset point, which is not the peak point. This causes to reduce the amplitude of the anticipated subcarriers, which can result to raise the Inter Carrier Interference (ICI) from the adjacent subcarriers (SCs). Figure 2 shows the impact of carrier frequency offset (CFO).

It is necessary to mention that although it is true that the frequency errors typically arise from a mismatch between the reference frequencies of the transmitter and the receiver local oscillators, but this difference is avoidable due to the tolerance that electronics elements have.

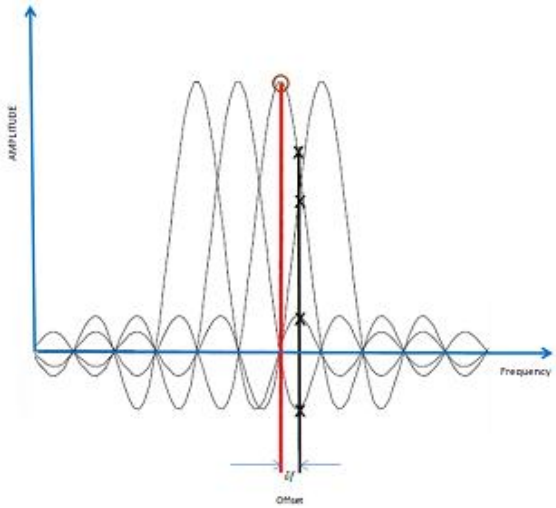

Figure 2: Frequency Offset

Therefore there is always a difference between the carrier frequencies that is generated in the receiver with the one that is generated in transmitter; this difference is called frequency offset f_{offset} i.e.

$$f_{offset} = f_c - f'_c$$

In where $f_c$is the carrier frequency in the transmitter and $f'_c$is the carrier frequency in receiver.

The OFDM systems are very sensitive to the carrier frequency offset (CFO) and timing, therefore, before demodulating the OFDM signals at the receiver side, the receiver must be synchronized to the time frame and carrier frequency which has been transmitted. Of course, In order to help the synchronization, the signals that are transmitted, have the references parameters that are used in receiver for synchronization. However, in order the receiver to be synchronized with the transmitter, it needs to know two important factors:

(i) Prior to the FFT process, where it should start sampling the incoming OFDM symbol from.

(ii) How to estimate and correct any carrier frequency offset (CFO).

A few other sources can cause frequency offset, such as frequency drifts in transmitter and receiver oscillators, Doppler shift, radio propagation and the tolerance that electronics elements have in local oscillators in transmitter and the receiver. When there is a relative motion between transmitter and receiver the Doppler can happen [4]. It is worth to mention the radio propagation talks about the behavior of radio waves when they are broadcasted from transmitter to receiver. In terms of propagation, the radio waves are generally affected by three phenomena whichare: diffraction, scattering and reflection.

The Doppler Effect (DE) defines as follows:

$$f_d = \frac{v.f_c}{c}$$

In where fdis Doppler frequency, c is the speed of light, and v is the velocity of the moving receiver. (i.e. 100 km/h). The normalized CFO (ε) is defined as follows:

$$\varepsilon = \frac{f_{offset}}{\Delta f}$$

In where Δf is the subcarrier spacing, it is necessary to mention that ε has two parts, one integer (ε_i) and one fractional (ε_f) so we have:

$$\varepsilon = \varepsilon_i + \varepsilon_f$$

$$\text{where } \varepsilon_i = \lfloor \varepsilon \rfloor$$

3. SYSTEM MODEL

In OFDM transmission scheme a wide-band channel divided into N orthogonal narrow-band sub-channels. N Point IFFT and FFT are used to implement OFDM Modulation and Demodulation. The transmitter maps the message bits *Xm* intoa sequence of BPSK or QAM symbols which are subsequently converted into an N parallel bit stream. Each of N symbols from the serial-to-parallel (S/P) conversion is modulated on the different sub-carriers.

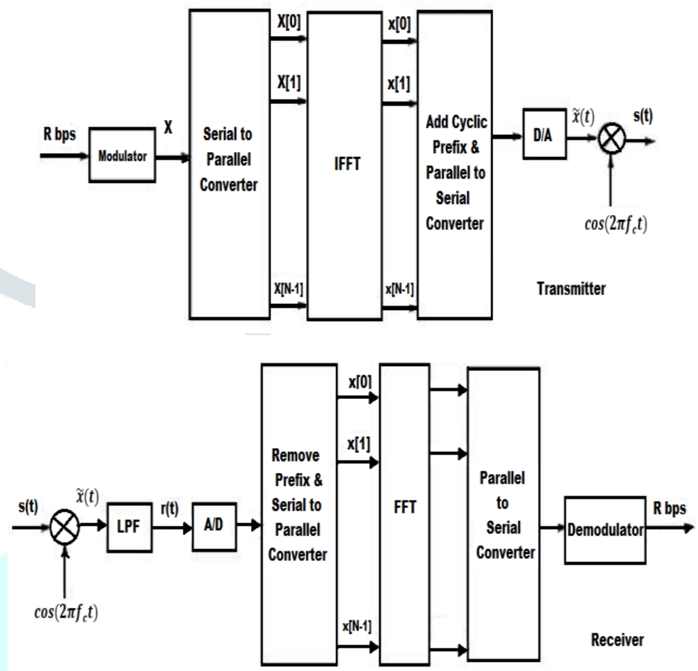

Figure 3: OFDM Transceiver blocks

IFFT of *s(t)* will be;

$$x(n) = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} X(i) e^{\frac{j2\pi ni}{N}}, \quad 0 \le n \le N-1$$

4. CFO ESTIMATION ALGORITHM &TECHNIQUES

CFO can produce Inter Carrier Interference (ICI) which can be much worse than the effect of noise on OFDM systems. That's why various CFO estimation and compensation algorithms have been proposed.For showing the importance of it, it is enough to mention that, by now the researchers have proposed numerous and various CFO estimation and compensation techniques and algorithms, which these methods can generally be categorized into two major branches:

1. Training based algorithm
2. Blind algorithm and Semi-blind algorithm

4.1 TRAINING BASED ALGORITHM

The training sequence can be designed the way that can limit the number of computation at the receiver side; therefore in general, these algorithms have a low computational complexity. On the other hand, the negative point of training based algorithm is the training sequences that must be transmitted from transmitter during its transmission. This can cause the reduction of the effectiveness of the data throughput.

4.2 BLIND AND SEMI-BLIND ALGORITHMS

Another algorithm that has been used is called Blind CFO estimation algorithm. In these algorithms by using the statistical properties of the received signal, the CFO will be estimated. Since the receiver doesn't have any knowledge of the signal that the transmitter has been sending, therefore the blind algorithms are considered to have a high computational complexity. The high computational complexity is the disadvantage of these algorithms. In compared with training based algorithm, blind algorithms have no need to the training sequences; therefore there is no training overhead for these algorithms. Further CFO estimation techniques can be subdivided in four major categories are as:

4.2.1 *CP Based:* With perfect symbol synchronization, a CFO of ξ results in a phase rotation of $2\pi n\xi/N$ in the received signal. Under the assumption of negligible channel effect, the phase difference between CP and the corresponding rear part of an OFDM symbol (spaced N samples apart) is $2\pi N\xi/N = 2\pi\xi$. Then, the CFO can be found from the phase angle of the product of CP and the corresponding rear part of an OFDM symbol, CFO estimation using CP based.

$$\tilde{\xi} = (1/2\pi)arg\{y_l^*[n]y_l[n+N]\}$$

n = -1, -2, ... *-Ng*. In order to reduce the noise effect, its average can be taken over the samples in a CP interval.

$$\tilde{\xi} = (1/2\pi)arg\left\{\sum_{n=-N_g}^{-1} y_l^*[n]y_l[n+N]\right\}$$

Arg() performed tan^{-1}(), the range of the CFO estimation is [-0.5+0.5] and mean square error performed by$\widetilde{\xi-\xi}$.

4.2.2 *Symbol Based:* Two identical training symbols are transmitted consecutively and the corresponding signals with CFO of ξ are related with each other. For an OFDM transmission symbol at one receiver with an assumption of the absence of noise the 2N Point sequence is [14].

$$r_n = \frac{1}{N}\sum_{k=0}^{N-1} H_k X_k e^{2\pi j(k+\xi)/N}$$

n = 0, 1, ... 2N-1, The *kth* element of the N Point DFT of the first N points for the above equation is;

$$R_{1k} = \sum_{n=0}^{N-1} r_n e^{-2\pi jkn/N}$$

k = 0, 1, 2, ... N-1,

The second half of the sequence is;

$$R_{2k} = \sum_{n=0}^{N-1} r_n + Ne^{-2\pi jkn/N}$$

$r_n + N = r_n e^{2\pi j\xi}, R_{2k} = R_{1k}e^{2\pi j\xi}$, including the AWGN noise,

$Y_{1k} = R_{1k} + W_{1k}$ &

$Y_{2k} = R_{1k}e^{2\pi j\xi} + W_{2k}$; k = 0, 1, 2, ... N-1.

Observe that between the first and second DFT symbols, both ICI and signal are altered in exactly the same way, by a phase shift proportional to frequency offset. Therefore, if frequency offset ξ is estimated using above observations, it is possible to obtain accurate estimation even when the offset is too large for satisfactory data demodulation [14].

$$\tilde{\xi} = (\frac{1}{2\pi})tan^{-1}\left\{\frac{\sum_{k=0}^{N-1} Im[Y_{2k}Y_{1k}^*]}{\sum_{k=0}^{N-1} Re[Y_{2k}Y_{1k}^*]}\right\}$$

The limit for accurate estimation by$|\xi|\leq 0.5$.

4.2.3 *Training Sequence Based:* CFO only within the range $|\xi|\leq 0.5$, Since CFO can be large at initial synchronization stage, we may need estimation techniques that can cover wider CFO range. The range of CFO estimation can be increased by reducing the distance between two blocks of samples for correlation. This is made possible by using training symbols that are repetitive with some shorter period. Let D represents the ratio of the OFDM symbol length to the length of a repetitive pattern. Let the transmitter sends the training symbols with D repetitive patterns in the time domain, which generated combo-type signal in the frequency domain after taking IFFT.

$$X_l[k] = \begin{cases} A_m & \text{if}, k = D.i, i = 0, 1, ...(N/D-1) \\ 0 & \text{eleswhere} \end{cases}$$

Where, *Am* represents an M-ary symbol and N/D is an integer and *xl*[*n*] and *Xl* [*n + N/D*] are identical. After receiving repetitive length data sequence, receiver can make CFO estimation as [16];

$$\tilde{\xi} = (D/2\pi)arg\left\{\sum_{n=0}^{N/D} y_l^*[n]y_l[n+N/D]\right\}$$

The estimation range in this technique is $|\xi|\leq D/2$, which becomes wider as D increases and number of samples for the computation of correlation is reduced by 1/D, which degrade the MSE performance of OFDM system. In other words, the increase in estimation range is obtained at the sacrifice of MSE (mean square error) performance.

$$\tilde{\xi} = (D/2\pi)arg\left\{\sum_{m=0}^{D-2}\sum_{n=0}^{N/D-1} y_l^*[n+mN/D]y_l[n+(m+1)N/D]\right\}$$

The MSE performance can be improved without reducing the estimation range of CFO by taking the average of the estimates with the repetitive patterns of the shorter period.

4.2.4 *Pilot Based:* Pilot tones inserted in the frequency domain and transmit every OFDM symbol for CFO tracking. The signals are transformed into *Yl*[*k*] *Nk*=0−1 and *Yl+D*[*k*] *Nk*=0−1 though FFT, from which pilot tones are extracted. After estimating CFO from pilot tones in the frequency domain, the signal is compensated with the estimated CFO in the time domain. In this process, two different estimation modes for CFO estimation are implemented: acquisition and tracking modes. In the acquisition mode, a large range of CFO including an integer CFO is estimated and in the tracking mode, only fine CFO is estimated. The integer CFO is estimated by [15].

$$\tilde{\xi} = (\frac{1}{2\pi T_{sub}})max(\xi)\left\{|\sum_{j=0}^{L-1} Y_{l+D}[p[j],\xi]Y_l^*[p[j],\xi]X_{l+D}^*[p[j]]X_l[p[j]]|\right\}$$

where L, p[j], and *Xl*[*p*[*j*]] denote the number of pilot tones, location of the *jth* pilot tone, and the pilot tone located at p[j] in the frequency domain at the *lth* symbol period [3].

5. CONCLUSION

CFO estimation is done by using four different techniques, one by using the phase difference between CP and the corresponding rear part of an OFDM symbol. Second by using the phase difference between two repetitive preambles. Third by using, training sequence with D integer i.e. ratio of the OFDM symbol length to the length of a repetitive pattern. Fourth one by estimation between pilots tones in two consecutive OFDM symbols. In all of the techniques we can categorized these into 3 major classes, data driven, blind and semi-blind.

Typically, three types of algorithms are used for frequency synchronization: algorithms that use pilot tones for estimation (data-aided), algorithms that process the data at the receiver (blind), and algorithms that use the cyclic prefix for estimation [5]. Among these algorithms, blind techniques are attractive because they do not waste bandwidth to transmit pilot tones [4]. However, they use less information at the expense of added complexity and degraded performance [4]. The general approaches to the problem of synchronization consist of a number of steps, including frame detection, carrier frequency offset and sampling error correction [7]. Frame detection is used to determine the symbol boundary needed for correct demodulation. Within each frame, the carrier frequency offset between the transmitter and the receiver causes an unknown phase shift factor [7]. Also we conclude that if a semi-blind technique is used which is having advantages of data-aided method and at the same time use of CP, this hybrid approach can be implemented and tested.

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