# Frequency Domain Equalization for Single Carrier Cyclic Prefix System

**By**

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A thesis submitted to the faculty of Electrical Engineering Department, Military College of Signals, National University of Sciences and Technology, Pakistan in partial fulfillment of the requirements for the degree of Master of Science in Telecommunication Engineering.

March 2010

# ABSTRACT

Broadband wireless access systems deployed in residential and business environment face hostile radio propagation environment due to multipath delay spread that extends over tens or hundreds of bit intervals. Multipath fading is a physical layer phenomenon and it has detrimental effects on the Quality of Service (QoS) parameters like Bit Error Rate (BER) and Packet Error Rate (PER) because of its stochastic nature.

Orthogonal Frequency Division Multiplexing (OFDM) is a recognized multicarrier solution to combat the multipath effects. An alternative to OFDM which gives better performance in some of the scenarios is the frequency domain equalized Single-Carrier (SC) modulated System. The application of frequency domain equalization (FDE) makes single carrier-modulated system a potentially valuable alternative to OFDM, especially about its robustness to RF implementation impairments. Usually SC modulated systems with FDE have decision feedback in time domain which involves convolution. As convolution is a slower process as compared to multiplication in frequency domain thus if Single Carrier modulated signal is equalized with decision feedback system in frequency domain can give better results.

In this thesis, simulations have been carried out to evaluate the performance of proposed frequency domain decision feedback equalization based single carrier modulated system for different wireless channel models and it is has been observed that the proposed method has increased computational speed and is less sensitive than OFDM to RF impairments such as power amplifier nonlinearities.

# DEDICATION

**To my loving Prophet (P.B.U.H) and parents.**

# ACKNOWLEDGMENT

All praise and thanks to Almighty Allah who has showered me with invaluable blessings throughout my life and has given me strength and spirit to complete this research work. I thank my parents whose love, care and prayers have enabled me to be, what I am. I also express my deepest appreciation to my colleagues whose unfeigned help and encouragement made the present work a reality.

I was truly blessed by being surrounded by extremely intelligent and supportive people. I would never have done it without their kind help. First, I am very grateful to my thesis advisor, Dr Adnan Rashidi and Co-Advisor, Dr. Shoaib A. Khan, who was always there for me. Discussions with him lead to many ideas described here. His most important contribution was his firm faith in me, even when I gave no reasons for it.

I also gratefully acknowledge the help and guidance provided by Lt Col Ateeq (Head of the Department, EE), Maj. Adnan Ahmed Khan and Asst Prof Fazal Ahmed. Without their personal supervision, advice and valuable guidance, completion of this thesis would not have been possible. I am extremely indebted to them for their support and continuous help during this work.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| SC | Single Carrier |
| TD | Time Domain |
| FD | Frequency Domain |
| CP | Cyclic Prefix |
| FDE | Frequency Domain Equalization |
| DFE | Decision Feedback Equalization |
| OFDM | Orthogonal Frequency Division Multiplexing |
| CDMA | Code Division Multiple Access |
| AWGN | Additive White Gaussian Noise |
| FFT | Fast Fourier Transform |
| IFFT | Inverse Fast Fourier Transform |
| ISI | Inter Symbol Interference |
| BER | Bit Error Rate |
| LOS | Line Of Sight |

*Chapter* **1**

# INTRODUCTION

## 2.1 *Introduction*

Future wireless communication must provide ever-increasing data transmission rates to satisfy the growing demands of wireless communication. As symbol rates increase, the Intersymbol Interference, caused by the band limited time dispersive channel, distorts the transmitted signal even more. High rate transmission over mobile radio channels leads to a problem of channel equalization in Single Carrier broadband systems as a major challenge. Single Carrier time domain equalization has become impractical because of the high computational complexity of needed transversal filters with a high number of taps to cover the maximum delay spread of the channel. This has lead to extensive research on spread spectrum techniques and multicarrier modulation. On the other hand, Single Carrier transmission has the benefit, especially for uplink, of a very simple transmitter architecture, which avoids, largely the peak-to-average power ratio problems of multicarrier like OFDM and CDMA techniques. In recent years, the idea of Single Carrier transmission in broadband wireless communications has been revived through the application of FD equalizers, which have clearly lower implementation complexity than time domain equalizers. Both Linear and Decision Feedback structures have been considered. It has been demonstrated that the Single Carrier Frequency Domain Equalization may have a performance advantage and that it is less sensitive to nonlinear distortion and carrier synchronization inaccuracies compared to multicarrier modulation [5]. The most common approach for FDE is based on FFT/IFFT transforms between the TD and FD. Usually, a Cyclic Prefix (CP) is employed for the transmission blocks. Such a system can be derived, by moving the IFFT from the OFDM transmitter to the receiver. FFT-FDE with CP are characterized by a flat fading model of the Subband responses, which means that one complex coefficient per Subband is sufficient for ideal linear equalization. This approach has overhead in data transmission due to the guard interval between symbol blocks. Another approach is to use overlapped processing of FFT blocks, which allows equalization without CP. This results in a highly flexible FDE concept that can be used for any Single Carrier system, including also CDMA [6].

## 2.2 *Fading*

In wireless communications, fading is deviation of the attenuation that a Carrier modulated telecommunication signal experiences over certain propagation media. The fading may vary with time, geographical position and radio frequency, and modeled as a random process. A fading channel is a communication channel that causes fading. All these fluctuation are due to a number of reasons, some of which are discussed below. In wireless systems, fading may be due to Multipath propagation, known to as Multipath induced fading, or due to shadowing from obstacles affecting the wave propagation phenomenon, sometimes known as shadow fading.

## 2.3 *Multipath*

While Multipath propagation will happen when a transmitted signal arrives at the receiver by two or more paths of different delays. Multipath propagation includes atmospheric ducting, ionospheric reflection, refraction and reflection from water bodies and terrestrial obstacles such as mountains and buildings. The effects of Multipath contain constructive and destructive interference and phase shifting of a signal. This is also known as *Multipath interference* (MPI). Multipath propagation causes signal attenuation and distortion. Those signal elements that propagate direct routes not only arrive earlier, but also suffer less absorption and diffusion attenuate the least and therefore, are the strongest. The signals that travel the least direct routes arrive last and are weakest. In wireless broadcast signaling, is the result of Multipath fading. Signals that propagate different paths but receive at approximately the same time can cancel each other. All of these elements contribute to Multipath fading.

## 2.4 *Flat Fading*

If coherence bandwidth of the channel is larger than the bandwidth of the signal, then, it is flat fading. The frequency components of the signal will experience the same magnitude of fading, when the spectrum over which the channel has constant gain and linear phase is wider than the bandwidth of the transmitted signal. As a result of which, the spectral information of the transmitted signal remains intact at the receiver but in deep fades, these channel attenuate the signal power heavily and require 20-30dB more transmit power for reliable communication to take place. These types of channels are also called as narrowband channels and the fading introduced by such channels can be mitigated either by increasing the transmit power or by applying the Equalization Techniques.

Increasing the transmit power is not a feasible solution for Single Carrier technique. Therefore, we can apply the equalization techniques to be leveraged in these communications to combat against the fading, which is investigated in this thesis. If there is some relative motion between the transmitter and the receiver, then Doppler spread is introduced in the signal spectrum and then the relationship between the Doppler shift and the signal bandwidth gives rise to either fast or slow fading.

## 2.5 *Frequency Selective Fading*

This type of fading is caused by the Multipath time delay spread. The channel undergoing frequency selective fading has coherence bandwidth (the range of frequencies over which the channel response is linear and constant) less than the bandwidth of the transmitted signal. The bandwidth of the signal is greater than coherence bandwidth of the channel. Such type of channels is also termed as wideband channels as the bandwidth of the transmitted signal is larger than that of the channel. This type of fading occurs due to the time dispersion of the transmitted symbols within the channel. This type of fading introduces Intersymbol Interference and their impact on the signal cannot be mitigated simply by increasing the signal power. A channel undergoing frequency selective fading approaches a probability of bit error of 0.5 with no regard to the received $E_b/N_0$ and this type of fading requires equalization techniques to reproduce the distorted signal or spatial diversity and hoping that one of the paths would not experience harsh fading conditions [19]. Specific modulation schemes such as OFDM and CDMA are well right to employing frequency diversity to provide robustness to fading. OFDM splits the wideband signal into many slowly modulated narrowband subcarriers, each showing to flat fading rather than frequency selective fading. This can be combated by means of error coding or simple equalization. Intersymbol Interference is minimized by introducing a guard interval between the symbols. CDMA uses the Rake receiver to treat with each echo separately. Frequency-selective fading channels are also dispersive, in that the signal energy related with each symbol is extended in time. This causes transmitted symbols to interfere with each other. Equalizers are designed for such channels to compensate the effects of the Intersymbol Interference.

## 2.6 *Small Scale Fading*

Wireless channels exhibit Multipath propagation due to which the receiver receives the randomly attenuated and delayed copies of the same signal, which is summed up at the receiver. If two components come in phase to each other, it results in the constructive interference and if the components are out of phase, they cancel out each other [18].

This constructive and destructive interference leads to dramatic fluctuations in the received signal over the distances of the order of half the wavelength, this phenomenon is termed as small-scale fading and it degrades the signal quality as shown in Figure 1.1.

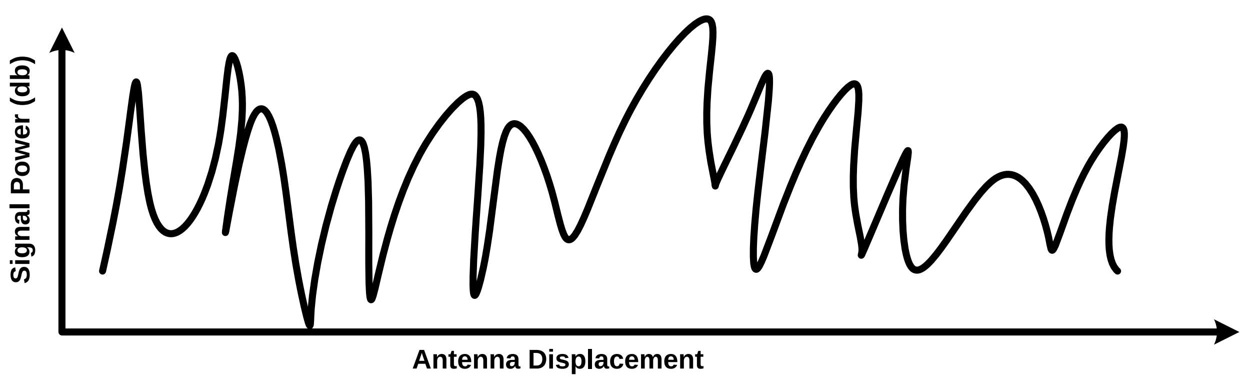


**Figure 1.1 Manifestation of Signal Fluctuation because of Fading**

There are different types of small scale fading which are based on different phenomenon. Two such fadings are Multipath Time Delay Spread and Doppler Spread. The types of fading caused by the Multipath time delay spread are classified under frequency selective fading and flat fading.

## 2.7 *Additive White Gaussian Noise Channel*

In communications, the information is given a single impairment for the additive white Gaussian noise (AWGN) channel model for which a linear addition of wideband or white noise with a constant spectral density (expressed as watts per hertz of bandwidth) and a Gaussian distribution of noise samples. The model does not link to the phenomena of fading, frequency selectivity, interference, nonlinearity or dispersion. However, it gives simple mathematical models, which are useful for gaining insight into the underlying behavior of a system before these other phenomena are considered. A generally accepted model for thermal noise in communication channels, is the set of assumptions that the noise is additive for which the received signal equals the transmit signal plus some noise, where the noise is statistically independent of the signal. The noise is white for which the power spectral density is flat, so the autocorrelation of the noise in Time Domain is zero for any non-zero time offset. Gaussian distribution is used for noise samples.

AWGN is assumed that the channel is Linear and Time Invariant. The AWGN further assumes that it is also frequency non-selective. Wideband Gaussian noise comes from many natural sources, such as the thermal vibrations of atoms in antennas, shot noise, black body radiation from the earth and other warm objects, and from celestial sources such as the Sun.

SC simulator in effected by noise in Gaussian process and noise samples are completely independent and the samples are uncorrelated. It is known as Memoryless channel because the propagated symbols are affected by noise independently.

### 2.8 *Rayleigh Fading Model*

To make Rayleigh Fading channel more realistic, it is added to the previously designed AWGN channel model. The main reason of choosing the Rayleigh Fading channel is that it is commonly used to describe the Multipath component of the environment or channel. This model brings in a Multipath channel and hence a channel estimator as well. The Rayleigh Fading channel becomes a more practical channel model just because of adding a Multipath environment to the AWGN component because the Multipath nature of the wireless is unavoidable.

***Chapter* 2**

# EQUALIZATION

### 3.1 *Equalization*

There is an ever-increasing demand from mobile phone subscribers for much higher data rates and, now recently, data services have become the hotspot in the 3G networks along with the traditional voice traffic. Almost all of the future systems primarily do not have any line of sight (LOS) component and experienced from severe multi-path resulting in large delay spread. In Multipath, transmitted signal reflections are received with different delays. This gives rise to ISI: the received symbol over a given symbol period experiences Interferences from other symbols that have been delayed due to multi-path propagation. Since increasing the signal power also increases the ISI, this interference gives rise to error problems, which is not depending on the signal power. If multi-path nature of the channel, due to, the delay spread is relatively larger with regard to the inverse signal bandwidth then it can origin severe signal distortion due to the time spreading of the arrived symbols. To combat against the distortive channel effects, to invert the FIR filter (time-invariant or time-varying) representing the channel, also known as equalizer is needed which moderates the effects of ISI caused by the delay spread.

## 3.2 *Time Domain Equalization*

A conventional anti-Multipath approach, which was pioneered in voice band telephone modems and has been applied in many other digital communications systems, is to transmit a Single Carrier, modulated by data using, for example, Quadrature Amplitude Modulation (QAM), and to use an adaptive equalizer at the receiver to compensate for ISI [3]. Its main components are one or more transversal filters for which the number of adaptive tap coefficients are of order of the number of data symbols spanned by the Multipath. For the above-mentioned 20 ms delay spread example, this would mean a transversal filter with at least 100 taps, and at least several hundred multiplication operations per data symbol. For tens of mega symbols per second and more than about 30-50 symbol ISI, the complexity and required digital processing speed becomes exorbitant, and this Time Domain equalization approach becomes unattractive.

## 3.3 *Frequency Domain Equalization*

A SC system is a traditional digital transmission scheme in which data symbols are transported at a fixed symbol rate serial stream of amplitude and phase-modulated pulses, which in turn modulate a sinusoidal carrier. A linear FDE performs receiver filtering in the frequency domain to minimize time domain Intersymbol Interference. Its function is the same as that of a time domain equalizer. However, for channels with severe delay spread, it is computationally simpler because equalization is performed on a block of data, and the operations on this block involve an efficient FFT operation and a simple channel inversion operation, just as is done in OFDM. Frequency Domain Equalization of Single Carrier modulated signals has been known since the early 1970's when combined with FFT processing and the use of a cyclic prefix (which makes convolutions appear circular), Single Carrier systems with Frequency Domain Equalization (SCFDE) have essentially the same low complexity as OFDM Systems [2].

### 3.4 *Comparison between FDE and TDE:*

The increasing demand for wireless multimedia and interactive Internet services is fueling intensive research efforts on high speed data transmission. A major design challenge for high speed broadband applications is the time dispersive nature of the terrestrial radio channel. The effects of Multipath propagation can be analyzed in the TD or in the FD. In the TD, when the time spread incorporated by the channel is larger than one symbol period, the interference among consecutive transmitted symbols, known as ISI, distorts the received signal. In the FD, if the communication bandwidth is larger than the so-called coherence bandwidth of the channel, then distinct frequency components of the transmitted signal will undergo different attenuations, resulting in a distortion. Data rates of tens of megabits per second over a wireless channel with a typical delay spread in the microseconds results in ISI results tens or even hundreds of symbols. High-speed broadband digital communication systems should be designed to handle such severe ISI. A famous approach to mitigate ISI in SC digital communication systems is the recovery for channel distortions through channel equalization in the TD at the receive side. Various Time Domain equalizers such as Maximum Likelihood Sequence Estimators (MLSEs), Linear Equalizers (LEs) and Decision Feedback Equalizers (DFEs) have been broadly studied in this scenario. Historically, TDEs were developed for ISI mitigation in narrowband wire line channels.

TDEs can be also deployed in broadband wireless communications; however, the number of operations per signaling interval grows linearly with the ISI span or with the data rates. A feasible approach to diminish time dispersion effects is MC transmission. Although a different terminology is invented due to rather independent developments of the two technologies, the main feature of MC systems is their ability to convert wideband channel into a large number of parallel narrowband subcarriers. In fact, in MC systems, the high-rate data stream is de-multiplexed and transmitted over a number of frequency subcarriers, whose channel distortion can be easily compensated for (i.e., equalized) at the receiver on a subcarrier-by-subcarrier basis.

The subcarriers are designed to have the minimum frequency division necessary to maintain orthogonality of their corresponding TD waveforms, therefore the signal spectra corresponding to the different subcarriers overlap in frequency. Therefore, the available transmission bandwidth is used very efficiently. MC techniques also enjoy the flexibility to assign variable constellation sizes and transmission powers [and hence multiple quality of service (QoS)] to their frequency sub-channels in addition to the ease by which certain frequency bands can be turned off. Although the main principles and some benefits offered by MC modulation have been established over 40 years ago, they have become very popular only recently with the availability of low-cost digital signal processors: since fast Fourier transform (FFT) operations need to be implemented for both modulation and demodulation. In particular, standardization bodies and major manufacturers for a wide range of applications have adopted coded OFDM. Examples include digital video broadcasting (DVB), digital audio broadcasting (DAB), wireless local area networks such as IEEE 802.1la/b/g/n, IEEE 802.16d/e, satellite digital audio radio services (SDARS) and power-line communications (PLC). OFDM is also a strong candidate for wireless personal area networks using ultra wideband technology as in IEEE 802.15.3 and for regional area networks using cognitive radio technology as in IEEE802.22. Moreover, OFDM has been considered for various applications involved in the third generation partnership project (3GPP) long-term evolution (LTE) and in 3GPP2 revolution. Despite its success, OFDM suffers from well-known drawbacks such as a large peak to average power radio (PAPR), intolerance to amplifier nonlinearities, and high sensitivity to carrier frequency offsets [17].

## 3.5 *Adaptive Equalization*

One of the practical problems in digital communications is Intersymbol Interference (ISI), which causes a given transmitted symbol to be distorted by other transmitted symbols. The ISI is imposed on the transmitted signal due to the band limiting effect of the practical channel and also due to the multi-path effects (echo) of the channel. One of the most commonly used techniques to counter the channel distortion (ISI) is linear channel equalization. The equalizer is a linear filter that provides an approximate inverse of the channel response. Since it is common for the channel characteristics to be unknown or to change over time, the preferred embodiment of the equalizer is a structure that is adaptive in nature. Conventional equalization techniques employ a pre-assigned time slot (periodic for the time-varying situation) during which a training signal, known in advance by the receiver, is transmitted. In the receiver the equalizer coefficients are then changed or adapted by using some adaptive algorithm (e.g. LMS, RLS, etc). Therefore, the output of the equalizer closely matches the training sequence. However, inclusion of this training sequence with the transmitted information adds an overhead and thus reduces the throughput of the system.

Therefore, to reduce the system overhead, adaptation schemes are preferred that do not require training, i.e., blind adaptation schemes. In blind equalization, instead of using the training sequence, one or more properties of the transmitted signal can be taken to estimate the inverse of the channel. The problem with blind adaptation techniques is their poor convergence property compared to traditional techniques using training sequences. Generally, a gradient descent based algorithm is used with the blind adaptation schemes. The most commonly used gradient descent based blind adaptation algorithm is the *Constant Modulus Algorithm* (CMA). CMA exploits the constant modularity of the transmitted signal for adapting the parameters of an equalizer. The counterpart of CMA is the *Least Mean Square* (LMS) algorithm that uses a training sequence for the adaptation process. Due to the knowledge of the transmitted sequence, the LMS algorithm, if convergent, will always converge to the two global minimum. Moreover, for a particular delay in the overall system, the LMS cost function is quadratic and provides only a single global minimum in the cost surface. Therefore, irrespective of the initialization, the LMS algorithm will converge to the global minimum. If the initialization is such that adaptation takes place in a major Eigen space only, the convergence is fast. For CMA based schemes, where the receiver does not know the transmitted sequence, any sequence with a constant phase offset with the input sequence may be considered to be the right sequence at the receiver, since, the phase shift does not change the constant modularity property of a signal. Due to this reason, unlike the LMS cost surface, the *Constant Modulus* (CM) cost surface will have multiple minima. Each of the minima will correspond to a unique phase shift. For a length $N$ equalizer, the number of minima of the CM cost surface is $N^2$; in other words, there are $N^2$ different phase shifts for which there exist solutions in the CM sense. For most practical purposes, all of the $N^2$ solutions are not equally acceptable. If the source sequence is a differentially encoded M-array PSK signal, for any transmitted sequence, M different sequences will be acceptable at the receiver [1]. The initialization of the equalizer determines the minimum point on the cost surface where to CMA will force the equalizer to converge. Therefore, depending on its initialization, an equalizer employing CMA may converge to a local or a global minimum. Another problem with the CMA algorithm is that the convergence rate is much slower than the convergence rate of any gradient descent algorithm using a training sequence [8].

*Chapter* **3**

# SINGLE CARRIER SYSTEM

## 4.1 *Single Carrier System*

In a basic Single Carrier system, the data block is modulated by using any modulation schemes with the addition of cyclic prefix and then it is transmitted. But on receiver side, the invert operation is performed on data block to remove interference that is inverse to the channel response and original data is obtained after detection process. As shown in a figure given below.

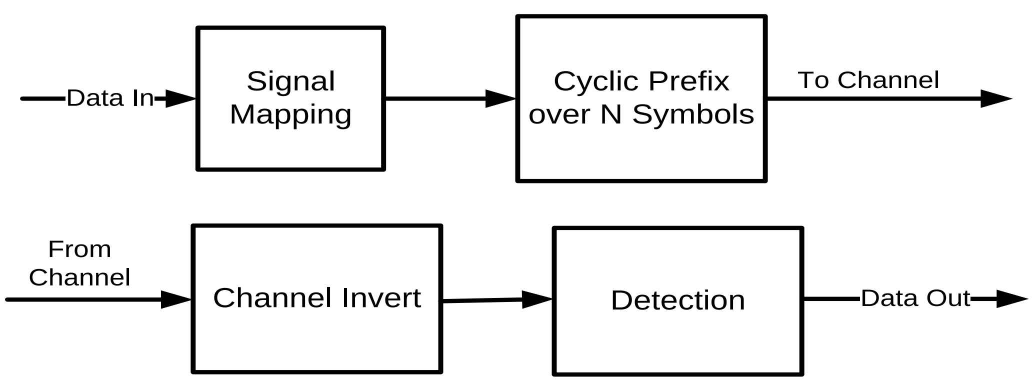


**Figure 3.1 Block Diagram of Basic Single Carrier System**

## 4.2 *Single Carrier Technology with FDE*

An alternative promising approach to ISI mitigation is the use of Single Carrier (SC) modulation combined with Frequency Domain Equalization (FDE). On the one hand, the complexity and performance of SCFDE systems is comparable to that of OFDM, while avoiding the above-mentioned drawbacks associated with multicarrier (MC) implementation.

On the other hand, FDE does not give an optimal solution to signal detection over ISI channels and OFDM offer more flexibility in the management of bandwidth and energy resources than SC systems, both in single user and in multiuser communications. All these contemplations have made the option between SCFDE and OFDM a strongly debatable issue in academic and industry. For this reason, we believe that SCFDE techniques need modifications as compared to given MC techniques. The first MC scheme was proposed in 1966, whereas the first approach to SCFDE in digital communication systems dates back to 1973 [18]. In the last decade, there has been a renewed interest in this area. The theoretical and practical gap between the two technologies is tightening. The principles of SCFDE with a particular focus on wireless applications and to present an up-to-date solution to get optimal results in the SCFDE area.

## 4.3 *Advantage of SCFDE*

An alternative low-complexity approach to ISI mitigation is the use of Frequency Domain equalizers (FDEs) in SC communications. Employing FD equalization systems are closely related to OFDM systems. In fact, in both cases digital transmission is carried out block wise, and relies on FFT/inverse FFT (IFFT) operations. Therefore, SC systems have similar FDEs complexity advantage as OFDM systems without the requirements of highly accurate frequency synchronization and linear power amplification as in OFDM. It is also worth noting that FDEs usually require a substantially lower computational complexity than their TD counter parts. In addition, SC systems with FD equalization can exhibit similar or better performance than coded OFDM systems in some scenarios [4].

The proposed a zero-forcing frequency domain block equalizer for Single Carrier systems with a guard interval of sufficient length. In Time Domain the insufficient guard interval, frequency domain redundancy approach takes subcarriers that do not transmit any data. After deriving sufficient conditions for zero-forcing equalization, that is, complete removal of inter-symbol and inter-carrier interference, we calculate the noise enhancement of the equalizer by evaluating the signal-to- noise ratio (SNR) for each subcarrier. The adaptive loading algorithm uses SNRs. Fixed error probability tell us how many bits are assigned to each subcarrier in order to achieve a maximum data rate. Therefore, redundancy in the Time Domain can be operate off for redundancy in the frequency domain resulting in a transceiver with a lower system latency time. Thus resulting equalizer have a low computational complexity.

For severe delay spread for channel Frequency Domain Equalization is computationally less complex than corresponding Time Domain equalization.

## 4.4 *SC with Cyclic Prefix*

In order to avoid problems on receiver side when receiving multi-path radio signals, each SC symbol is extended by a ‘cyclic prefix’. At the transmitter, the last part of each symbol is inserted at the start of the same symbol. At the receiver, the data contained in the cyclic prefix of the SC symbol is ignored after synchronization. If two signals are received due to multi-path then two consecutive symbols in the delayed signal should occur within the cyclic prefix and cause no problem. This is a method to avoid multi-path signals causes Inter Symbol Interference (ISI). The channel impulse response has a length $L$. The Cyclic prefix is simply of copying the last *25%* values from each symbol and appending them in the front of the symbol. The actual data at the beginning of the next symbol does not affect. This cyclic prefix (or guard interval) slightly reduces the effective data throughput as this duplicates data already present but the result is a robust signal that is robust to data errors caused by multi-path reception.

In SC system, first p symbols from data block are used to append at the end of M symbols data block. In addition, by repeating the first symbols at the last, the first real "data" symbols experience overlap with the "end" of the symbols, just as in cyclic convolution. Since cyclic convolution directly corresponds to multiplication in the frequency domain. It is broken back into the parallel symbols and the prefix is simply discarded.

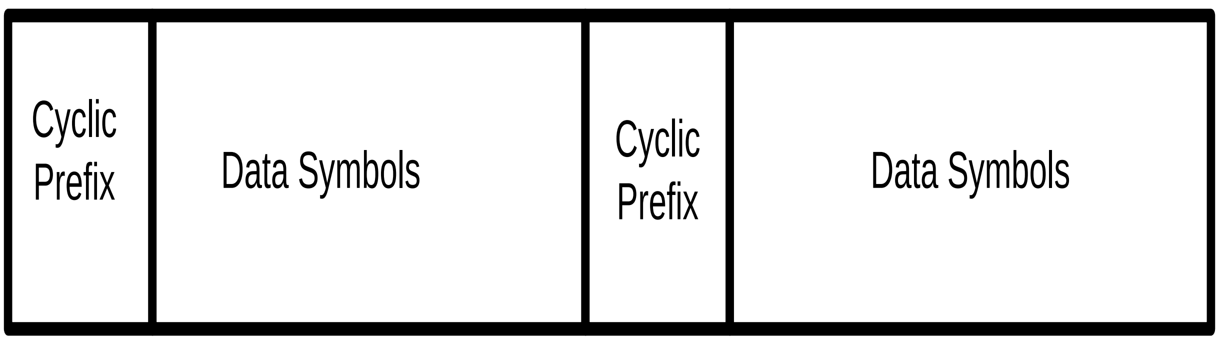


**Figure 3.2 Cyclic Prefix Insertions**

## 4.5 *Channel Estimation*

FFT-FDEs can be implemented by using adaptive channel equalization algorithms to adjust the equalizer coefficients. However, we focus here on channel estimation based approach, where the equalizer coefficients are calculated at regular intervals based on the channel estimates and knowledge of the desired filter frequency response [7]. In the performance studies, I have utilized a basic, least mean square method for channel estimation using training sequences.

The radio channels in mobile radio systems are usually Multipath fading channels, which are causing Intersymbol Interference (ISI) in the received signal. To remove ISI from the signal, many kinds of equalizers can be used. Detection algorithms based on trellis search (like MLSE or MAP) offer a good receiver performance, but still often not too much computation. Therefore, these algorithms are currently quite popular. However, these detectors require knowledge on the channel impulse response (CIR), which can be provided by a separate channel estimator.

Usually the channel estimation is based on the known sequence of bits, which is unique for a certain transmitter and which is repeated in every transmission burst. Therefore, the channel estimator is capable to estimate Channel Inverse Response for each sequence is separated by exploiting the known transmitted bits and the corresponding received samples. In this report, we give first some general background information on channel estimation. Then we introduce Least squares (LS) channel estimation techniques. Finally, conclusions are displayed in form graphs [1].

***Chapter* 4**

# ANTI-MULTIPATH APPROACHES

## 7.1 *Anti-Multipath Approaches*

For channel responses spanning over tens or hundreds of symbols, and for wider bandwidths and higher bit rates, practical modulation alternatives are:

(1) OFDM (Orthogonal Frequency Division Multiplexing).

(2) Single Carrier modulation with receiver equalization done in the Time Domain.

(3) Single Carrier modulation with receiver equalization in the frequency domain. Any of these Anti-Multipath approaches can be combined with antenna diversity at the transmitter and the receiver [4].

## 7.2 *Overview of OFDM*

OFDM stands for Orthogonal Frequency Division Multiplexing. OFDM is an arrangement of multiplexing and modulation technique. In OFDM a wideband channel is split into narrow band channel. These narrow band channels are modulated by the data and then these narrow band carriers are multiplexed to create OFDM carrier. In OFDM system, the subcarriers are orthogonal to each other. The independent sub-channels are multiplexed by Frequency Division Multiplexing called multicarrier transmission. A multi-carrier modulation is used in OFDM system, based on the discrete Fourier transform in which a high bit rate stream is divided into a large number of low data rate sub-channels each of which modulates a Single Carrier. Sub-carriers are spaced orthogonal to each other. OFDM has proposed for digital mobile radio and wireless multimedia communication. The major idea engaged in OFDM is orthogonality of the subcarriers. The orthogonality of subcarrier permits instantaneous transmission on subcarrier which are closely placed in the spectrum without interference from each other. OFDMA is a derived technology, which can be used for shared access.

It has several drawbacks including a large peak-to-average power ratio (PAPR), intolerance to amplifier nonlinearities, and high sensitivity to carrier frequency offsets (CFOs).

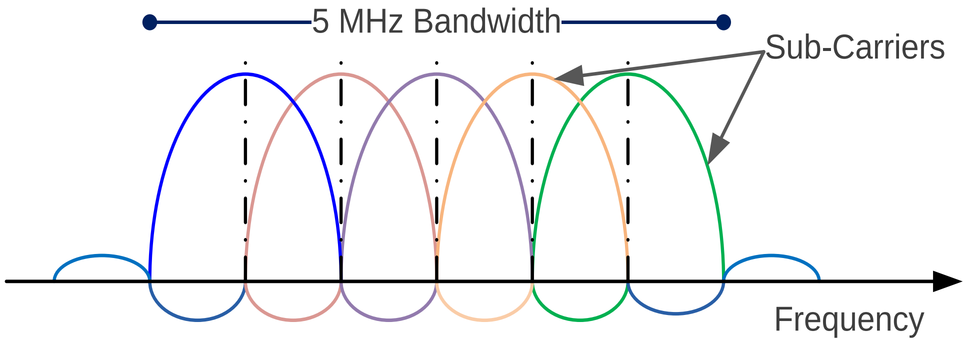


**Figure 4.1 Sub-Carriers Formation in OFDM System**

## 7.3 *Comparison of OFDM and SC Technique*

Orthogonal frequency division multiplexing (OFDM) has been recently adopted by major manufacturers and by standardization bodies for a wide range of wireless and wire line applications ranging from digital video/audio broadcasting to power-line communications. The major virtues of OFDM are:

- Its aim to Multipath propagation providing a possible low-complexity and optimal solution for Intersymbol Interference (ISI) mitigation.
- The option of accomplishing channel capacity of the transmitted signal is adapted to the state of the communication channel (i.e., if bit-loading and energy procedures are adopted).
- Therefore, OFDM has become popular for the physical layer of choice for broadband communications standards.

OFDM suffers from several drawbacks including

- A large peak-to-average power ratio (PAPR).
- Intolerant to amplifier nonlinearities.

- High sensitive to carrier Frequency Offsets.

An alternative promising approach to ISI mitigation is the use of Single Carrier (SC) modulation combined with Frequency Domain Equalization (FDE). On the one hand, the complexity and performance of SCFDE systems is comparable to that of OFDM while avoiding the above-mentioned drawbacks associated with multicarrier (MC) implementation. On the other hand, FDE does not give an optimal solution to signal detection over ISI channels and OFDM offer more flexibility in the management of bandwidth and energy resources than SC systems, both in single user and in multiuser communications [20].

## 7.4 *Why use SCFDE instead of OFDM*

SCFDE systems have several RF implementation advantages over OFDM. In particular, a disadvantage of OFDM is that its RF signal suffers from high envelope fluctuations due to the transmission of many sub-carriers. To avoid significant spectral re-growth [10] or BER degradations resulting from nonlinear distortion [11], OFDM systems require highly linear transmitter power amplifiers and/or several dB more power backoff than do comparable Single Carrier systems with the same average power output [12]. For given cell coverage requirements, this translates into significantly higher RF front-end costs for OFDM systems, especially for mobile and portable terminals [13]. For given power amplifier specification, it translates into lower cell coverage. This power back off penalty is particularly vital for subscribers near to edge of a cell, with large path loss, with lower level modulation such as BPSK or QPSK modulation must be used [9]. A further sensitivity of OFDM, not shared to the same degree by Single Carrier, is phase noise and frequency offsets, the close spacing in frequency of its subcarriers. This sensitivity leads to tighter local oscillator requirements for OFDM systems [14], [13].

## 7.5 *Doppler Effect*

The Doppler effect is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves [7]. In mobile wireless communication scenario, Doppler effect is attributed to the relative movement of the surrounding objects as well as the transmitter and receiver. It leads to fast phase oscillation of the received signals on multiple paths, thus accelerates the time variation of the channel distortion.

## 7.6 *Wireless Channel Impairments*

The most important thing while designing any communication system is to consider the channel over which the transmitted signal will propagate. Knowledge of impairments or deformations the transmitted signal is encountering while riding on the channel is very important to recover the destructive effects of the channel. Thus, the designing of the transmitter and receiver totally depends upon impairments the transmitted signal will fail. For designing a radio system, it is important to check what kind of wireless channel conditions the propagated signal will encounter. The Additive White Gaussian Noise (AWGN) is an ideal channel for some wireless systems for example line of sight microwave communication, satellite communication.

Complex notation of the transmitted signal $S(t)$ is given as:

$$S(t) = \mathrm{Re}\left\{g(t)e^{j2\pi f_c t}\right\} \tag{4.1}$$

$g(t)$ is the baseband part of the transmitted signal and is given as:

$$g(t) = |g(t)|e^{j\phi(t)} = R(t)e^{j\phi(t)}$$

(4.2)

$R(t)$ depends on the transmit power and is the amplitude of the transmitted waveform. During the course of transmission through the channel, the RF energy gets attenuated due to different propagation mechanisms and the baseband signal $g(t)$ gets attenuated and delayed by a parameter $\alpha(t)e^{j\theta(t)}$ and the baseband waveform becomes

$$g(t) = \alpha(t)R(t)e^{j(\phi(t)-\theta(t))} \qquad (4.3)$$

This thesis is concerned with investigating the fading effects in which signal power fluctuates rapidly over small distances and small intervals. If power fluctuations are taken into account, the amplitude of the baseband signal becomes

$$\alpha(t)R(t) = m(t) \times r_0(t) \times R(t) \qquad (4.4)$$

$m(t)$: Large Scale Fading Component

$r_0(t)$: Small Scale Fading Component

## 7.7 *Doubly Selective Channels*

Wireless communications operate through electromagnetic radiation from the transmitter to the receiver. The communication medium, commonly referred as the channel, usually distorts the signal based on its propagation characteristics. Two important factors which characterize the distortion effects of the channel are Multipath fading and Doppler effect. Multipath fading is the phenomenon in which the transmitted signal arrives at the receiver via multiple propagation paths at different delays due to reflection, diffraction and scattering of the radio waves. It results in a wide variation of the received signal strength, since the multiple signals arriving at the receiver may add up constructively or destructively. The Doppler effect, named after Christian Doppler, is the change in frequency and wavelength of a wave that is perceived by an observer moving relative to the source of the waves [7].

In mobile wireless communication scenario, Doppler effect is attributed to the relative movement of the surrounding objects as well as the transmitter and receiver. It leads to fast phase oscillation of the received signals on multiple paths, thus accelerates the time variation of the channel distortion. Future wireless communication services featuring high-data-rate and high-mobility can aggravate the Multipath and Doppler effect. In digital communication systems, for most of the channels, the discrete information bearing symbols are modulated with a continuous pulse shape and transmitted across the channel [8].

In most cases, the pulse shapes are localized in time and frequency so that transmission of each symbol consumes a small tile in the time-frequency plane. For high data rate transmission, the duration of the pulse becomes small and comparable to the Multipath delay, thus ISI occurs and the channel distortion is called frequency-selective. In high mobility scenarios, the channel response varies significantly in the signaling duration due to Doppler effect, thus the channel distortion becomes time-selective within a single processing block. Channels whose response are both time and frequency selective are commonly referred as doubly-selective channels.

Theoretically, the doubly selective channel can be modeled as a linear time-varying system [9]. When the surrounding objects are stationary, the input and output relationship between transmitter and receiver can be represented as a linear time-invariant system with the impulse response.

$$c(\tau) = \sum_{\ell=1}^{N_\ell} c_\ell \delta(\tau - \tau_\ell) \tag{4.5}$$

where $c_\ell$ and $\tau_\ell$ are the attenuation and propagation delay of the $\ell$-th path respectively. This model is widely adopted for description of Multipath frequency-selective channel. When there is relative movement between the surrounding objects including transmitter and receiver, the attenuation and delay of the $\ell$-th path vary with time. Therefore, the impulse response of the channel becomes

$$c(t,\tau) = \sum_{\ell=1}^{N_\ell} c_\ell(t)\delta(\tau - \tau_\ell(t)) \tag{4.6}$$

This is the continuous time model for a doubly selective channel.

Doppler spread and delay spread are two important quantities that measure the time selectivity and frequency selectivity of the channel respectively. The Doppler shift of the $\ell$-th path is defined as $f_c \frac{d\tau_i(t)}{dt}$ , where $f_c$ is the carrier frequency. The Doppler spread $f_d$ is defined as the largest difference between the Doppler shift of all paths.

$$f_d = \max_{i,j} f_c \left| \frac{d\tau_i(t)}{dt} - \frac{d\tau_j(t)}{dt} \right| \tag{4.7}$$

Larger $f_d$ implies that the channel varies more rapidly in time. The delay spread (or Multipath spread) is defined as the difference in the propagation time between the longest and shortest path. Thus,

$$T_d := \max_{i,j} f_c \left| \tau_i(t) - \tau_j(t) \right| \tag{4.8}$$

When $T_d$ is larger, the Multipath effect is more evident.

***Chapter* 5**

# SINGLE CARRIER SYSTEM WITH FDE

## 9.1 *Single Carrier System Equalized in Frequency Domain Design*

In conventional SCFDE, the data stream is divided into blocks at the transmitter, similar to OFDM, inserting a cyclic prefix between successive blocks for equalization purposes [7], [8]. This guard interval mitigates inter-block interference (IBI) induced by the time dispersion of the channel, while the task of the frequency domain equalizer is to reduce ISI within the individual blocks. The structure of one transmit block, which consists of the original sequence of $N$ symbols with duration $T_{FFT} = NT$ ($T$ is the duration of one symbol), extended with a CP with duration $T_G$ , containing $N_G$ guard symbols.

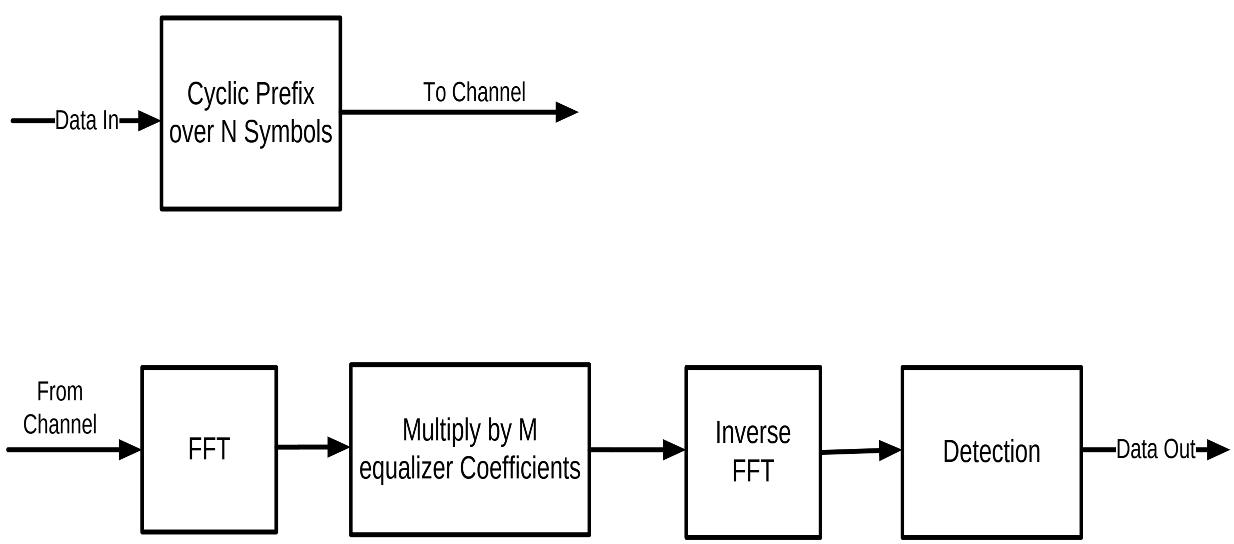


**Figure 5.1 Single Carrier System with FDE**

## 9.2 *Bernoulli Random Binary Data Generator*

It is used as the data source. This building block produces random binary data by means of a Bernoulli distribution. The Bernoulli distribution with factor ’p’ generates zeros with probability p and ones with probability (1 - p). The probability of a zero for example ’p’ is specified in block and can be a real number between 0 and 1. Thus, any random series of bits can be produced to simulate a data source.

## 9.3 *Training Sequence*

Training sequence is a known bits pattern on both transmitter and receiver sides. It is concatenated with original data to form a matrix. This known bits pattern is used as input for adaptive equalization on receiver side. The channel estimation is made with the help of this known bits pattern inside the equalizer.

## 9.4 *Baseband Modulator*

Like all modulation schemes, QAM conveys data by changing some aspect of a carrier signal, or the carrier wave, (usually a sinusoid) in response to a data signal. In the case of QAM, the amplitude of two waves, they are 90 degrees out-of-phase with each other (in quadrature) are changed (modulated) to represent the data signal. Phase modulation and phase-shift keying can be considered as a special case of QAM, where the magnitude of the modulating signal is a constant, with only the changing phase.

Due to large path loss, where lower-level modulation schemes such as binary PSK (BPSK) or QPSK and 16-QAM modulation must be used.

## 9.5 *Cyclic Prefix insertion*

In SC system, first p symbols from data block are used to append at the end of M symbols data block. In addition, by repeating the first symbols at the last, the first real "data" symbols experience overlap with the "end" of the symbols, just as in cyclic convolution. Since cyclic convolution directly corresponds to multiplication in the frequency domain, it is broken back into the parallel symbols and the prefix is simply discarded. It has two main functions

- It prevents Intersymbol Interference contamination of blocks.
- It makes the received block appear to be periodic with period *M*. This results the appearance of circular convolution, which is important for proper functioning of the FFT operation.

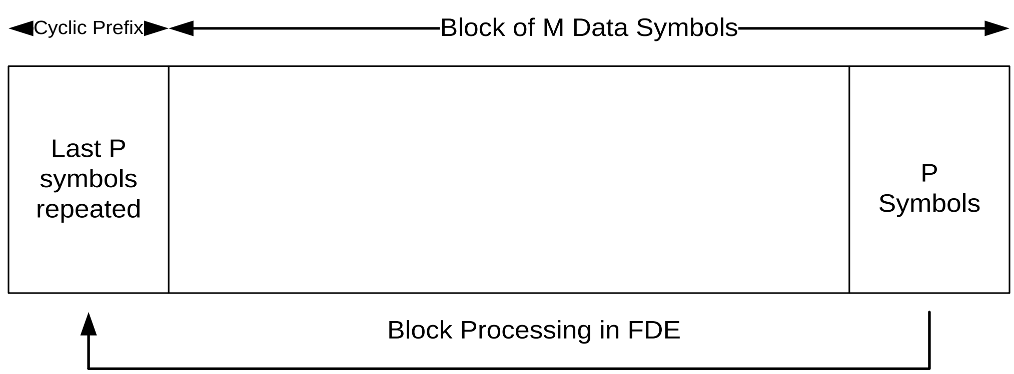


**Figure 5.2 Cyclic Prefix insertion for SC System**

## 9.6 *FFT*

To work in frequency domain, received data block is passed through FFT block. The data block $[Y_M]$ arrived to the receiver is first FFT-processed, and then the influence of the frequency-selective channel impulse response is eliminated by a simple channel inversion operation.

## 9.7 *Frequency Domain Equalizer*

This stage gives the channel inverse response. This block eliminates the influence of the frequency-selective channel by a simple channel inversion operation. In adaptive SCFDE, the adaptation of FDE transfer function can be done using least mean square (LMS). In FDE each sample of an incoming block in multiplied by its corresponding equalizer coefficients and desired gain is applied to remove interference.

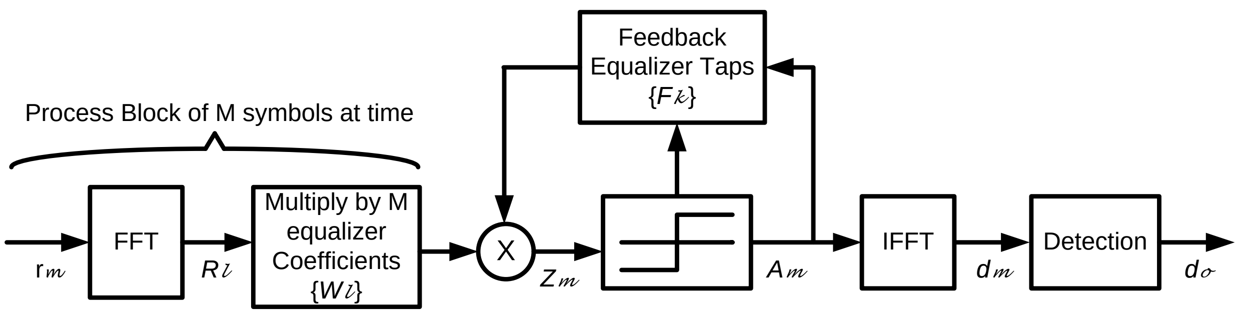


**Figure 5.3 SC-FDE *Decision Feedback Equalizer***

## 9.8 *SCFDE with Decision Feedback Block*

For more better results a Decision feedback equalization (DFE) block is used in conjunction to frequency domain equalizer. That gives better performance for frequency-selective radio channels than linear equalization [8]. In conventional Time Domain DFE equalizers, symbol-by-symbol data symbol decisions are made, filtered, and immediately fed back to remove their interference effect from subsequently detected symbols. Because of the delay inherent in the block FFT signal processing, this filtered decision feedback can be done in a frequency domain DFE, which uses frequency domain filtering of the fed-back signal. A combined frequency domain DFE approach would be to use frequency domain filtering for the forward filter and as well as DFE. It utilizes feedback adaptive equalizer for the feedback part. The feedback equalizer is relatively simple in any case, since it reduces the complexity of receiver portion as compared to hybrid frequency-Time Domain equalizer. Complexity is minimized by making the feedback taps few in number and sparse, corresponding to the largest channel impulse response echoes. This also tends to minimize possible DFE error propagation problems [9].

## 9.9 *IFFT*

An inverse FFT results the equalized signal to the Time Domain prior to the detection of data symbols.

## 9.10 *Detection*

In detection process, low-pass original data is acquired by demapping of data. After demodulation a baseband signal is retrieved.

*Chapter* **6**

# *CONCLUSION AND RESULTS*

## 10.1 *BER Performance for AWGN Channel and Multipath Channel*

Frequency Domain Equalizer with decision feedback gives much better results in AWGN channel environment as compared to Multipath channel environment with modulation schemes BPSK, QPSK and 16-QAM.

## 10.2 *Bit Error Rate Implementation (BER)*

BER is used as performance metric for all the sets of simulations, the packets of 192 bits with 64 bits of Training Sequence. Total block have 256 bits, that were sent on the transmission channel and received at the receiver. The bits in error were counted. The threshold at which no further packets are sent was set at 8 million bits. At this point, the BER is estimated by relative frequency of the occurrence of 8 million errors to the total number of bits transmitted in the process.

## 10.3 *Comparison Curve between FDE and FDE Decision Feedback*

BER performance gets apparently better with increase in Average SNR using FDE with Decision Feedback as compared to simple FDE.

## 10.4 *Contributions*

The primary aim of this thesis is to implement SCFDE system to mitigate and combat against ISI, which is alternative to technique OFDM and performs better in some of the scenarios. Total equalization with decision feedback is done in frequency domain to reduce receiver computational complexity. As in hybrid frequency-time equalization model decision feedback in Time Domain performs separate computation for each data symbol. In frequency domain feedback block performs computation for a whole block.

Finally SCFDE with FDE in frequency Domain is the best technique to combat against ISI, it is less computationally complex as compared to SC hybrid frequency-time equalization, less PARP as compared to OFDM, less sensitive to carrier frequency offsets and it is tolerant to non-linearities of amplifier.

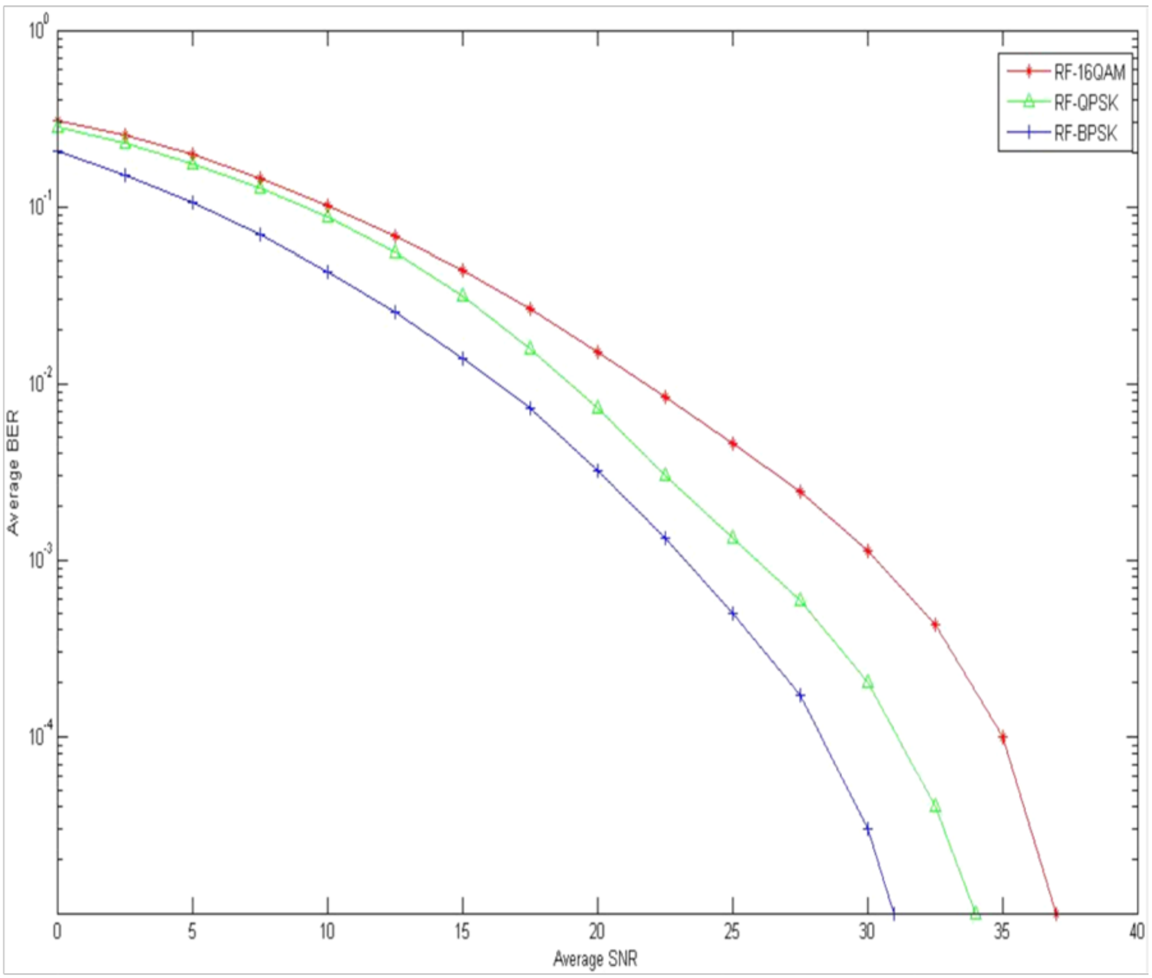


**Figure 6.1 Multipath Channel BER Performance for BPSK, QPSK and 16-QAM**

### 6.4.1 BER Performance for BPSK, QPSK and 16-QAM (Multi-Path Channel)

In multi-path channel environment, the BER performance degraded due to dispersive behavior of environment. The graph shows the BER performance for BPSK, QPSK and 16-QAM over Multipath channel.

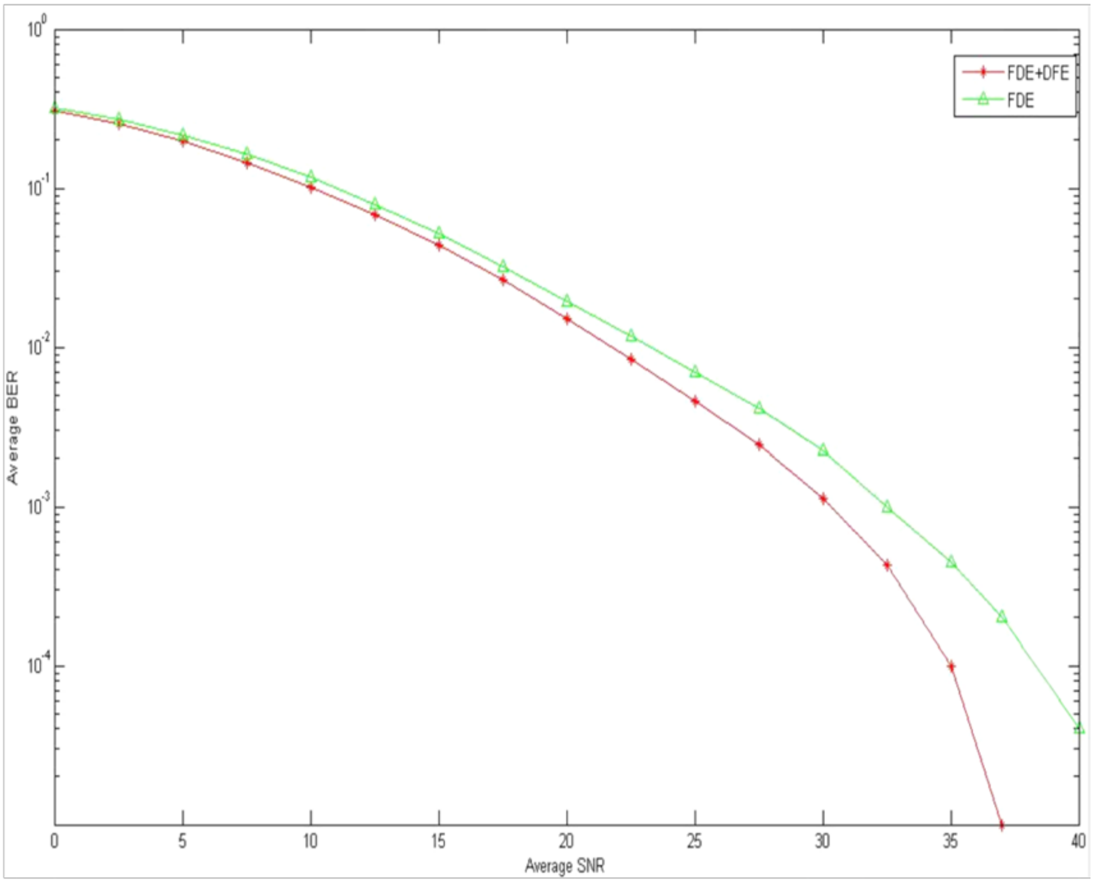


**Figure 6.2 Comparison BER Performance between Simple FDE and Equalization with Decision Feedback in Frequency Domain**

### 6.4.2 BER Performance for Single Carrier System with FDE with DFE and without DFE

The Single Carrier system with frequency domain equalizer with decision feedback block can almost remove the interference between symbols. But simple frequency domain equalizer cannot exactly remove the interference from symbols. That why Single Carrier system with frequency domain equalizer with decision feedback block has better results as compared to SC FDE system without DFE.

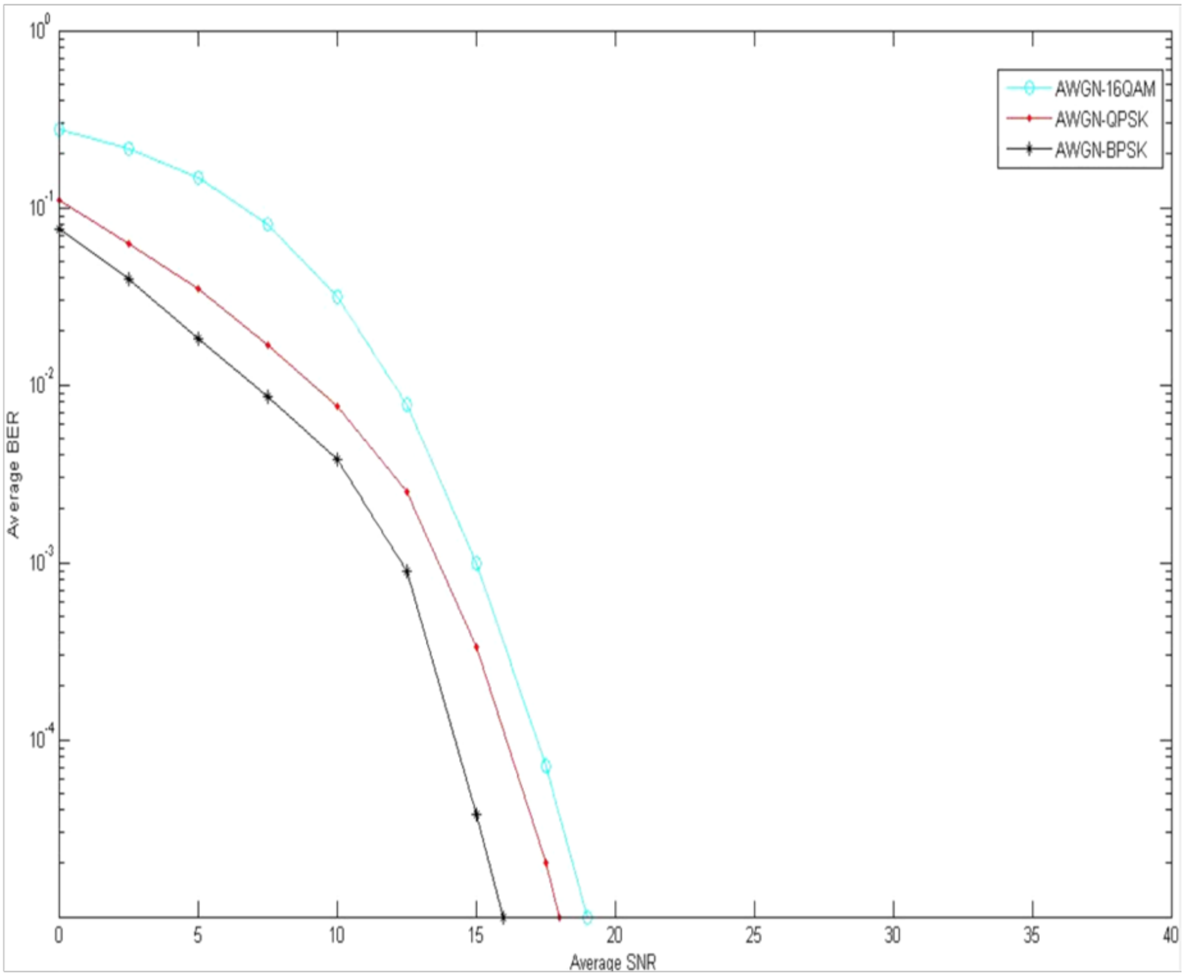


**Figure 6.3 AWGN Channel BER Performance for BPSK, QPSK and 16-QAM**

### 6.4.3 BER Performance for BPSK, QPSK and 16-QAM (AWGN Channel)

In AWGN channel environment, the BER performance is better as compared to Multi-Path channel environment, because it only a noisy channel and there is no fading. The graph shows the BER performance for BPSK, QPSK and 16-QAM over AWGN channel.

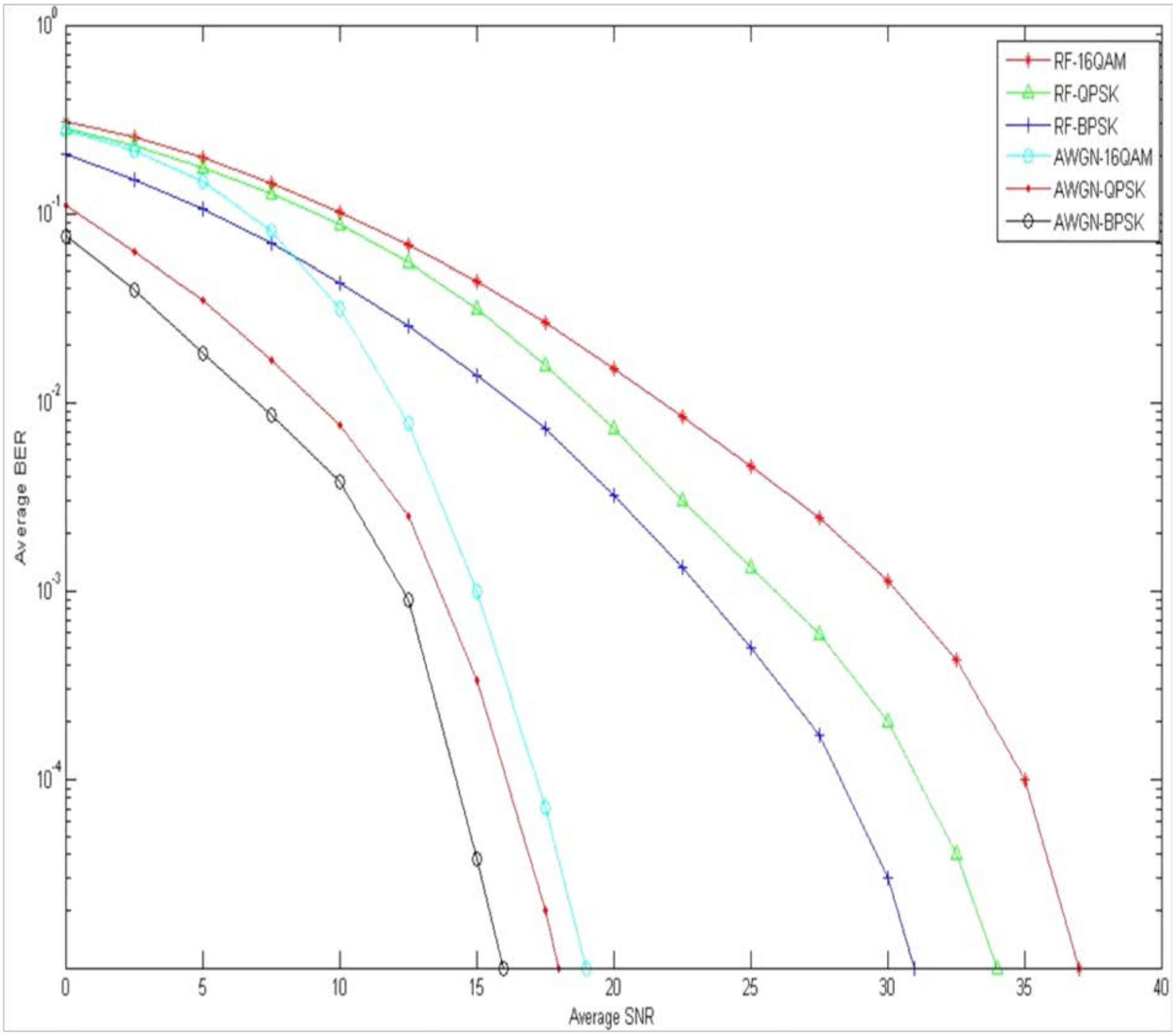


**Figure 6.4 Comparative BER Performances for AWGN Channel and Multipath Channel with BPSK, QPSK and 16-QAM**

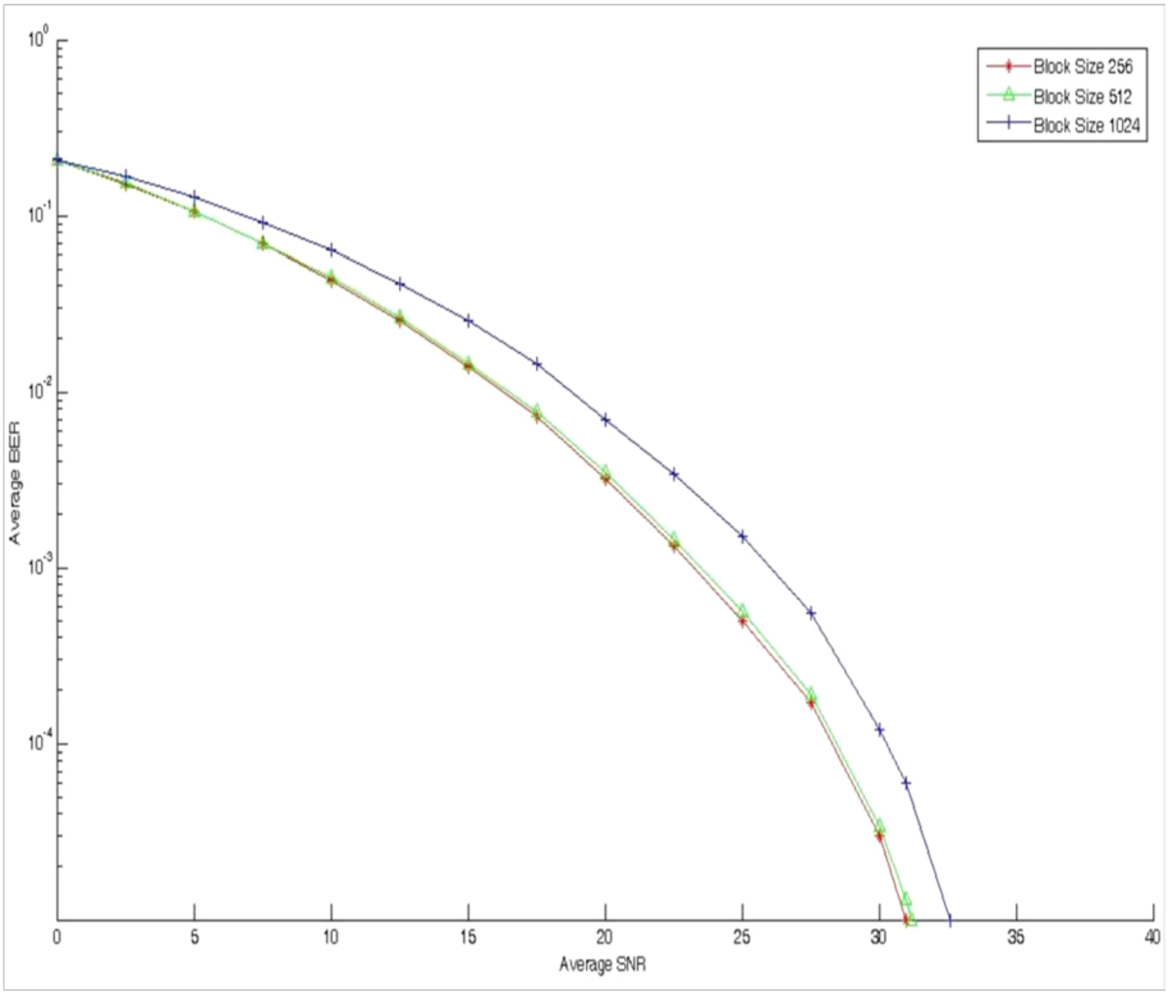


**Figure 6.5 BER Performance for Different Block Sizes**

### 6.4.4 BER Performance for different block sizes

The BER performance is calculated for different Block sizes as shown in above figure (no. of symbols in each Block are 256, 512 and 1024). As 256 symbols block and 512 symbols block have almost same BER performance, but 1024 symbols block have little high BER as compared to other block sizes. Because it is bit difficult for system to remove interference from large block. That why Single Carrier system performance degraded for large block sizes.

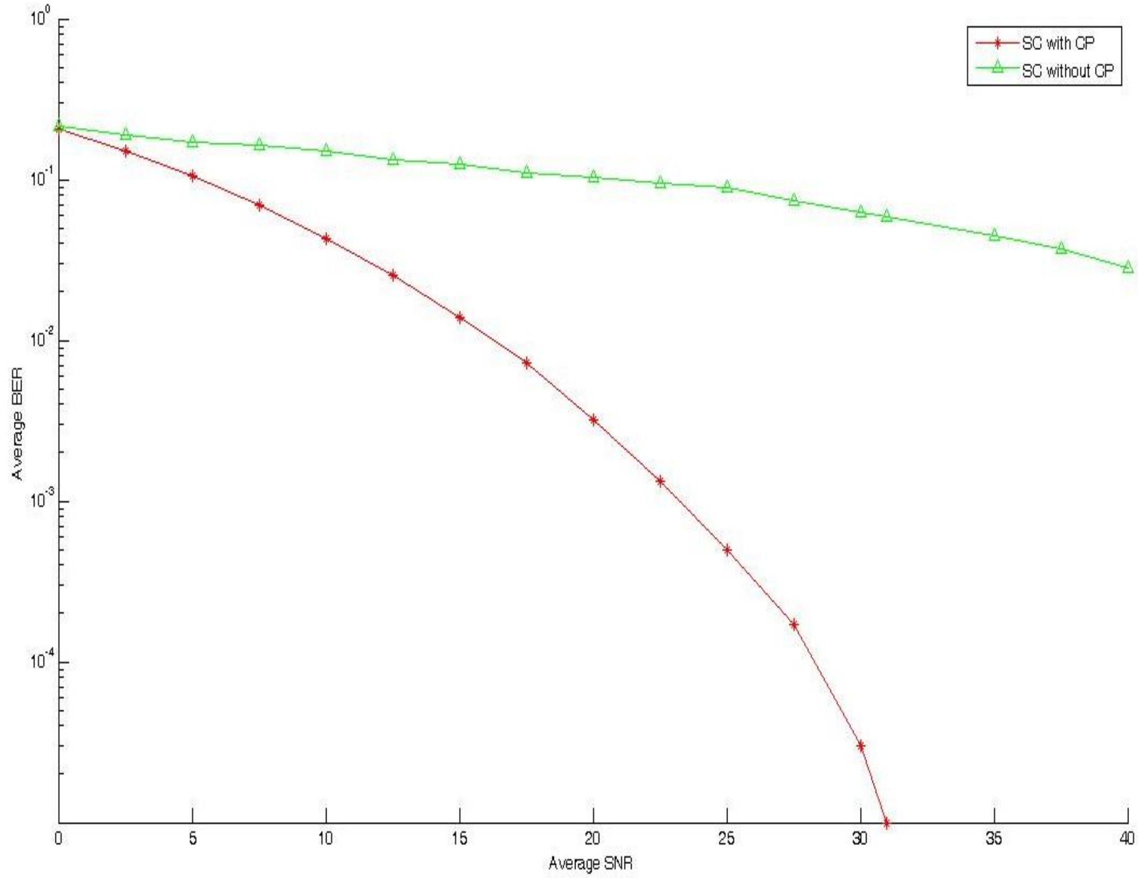


**Figure 6.6 Comparison curve between SC without Cyclic Prefix and SC with Cyclic Prefix for BPSK Modulation**

### 6.4.5 BER Performance for Single Carrier with CP and without CP

From above results Single Carrier without cyclic prefix have very high rate of inter-block interference as compared to system with cyclic prefix. Therefore, it is not possible to use Single Carrier technique without cyclic prefix in practical environment. BPSK, QPSK and 16-QAM modulation schemes have almost same results.

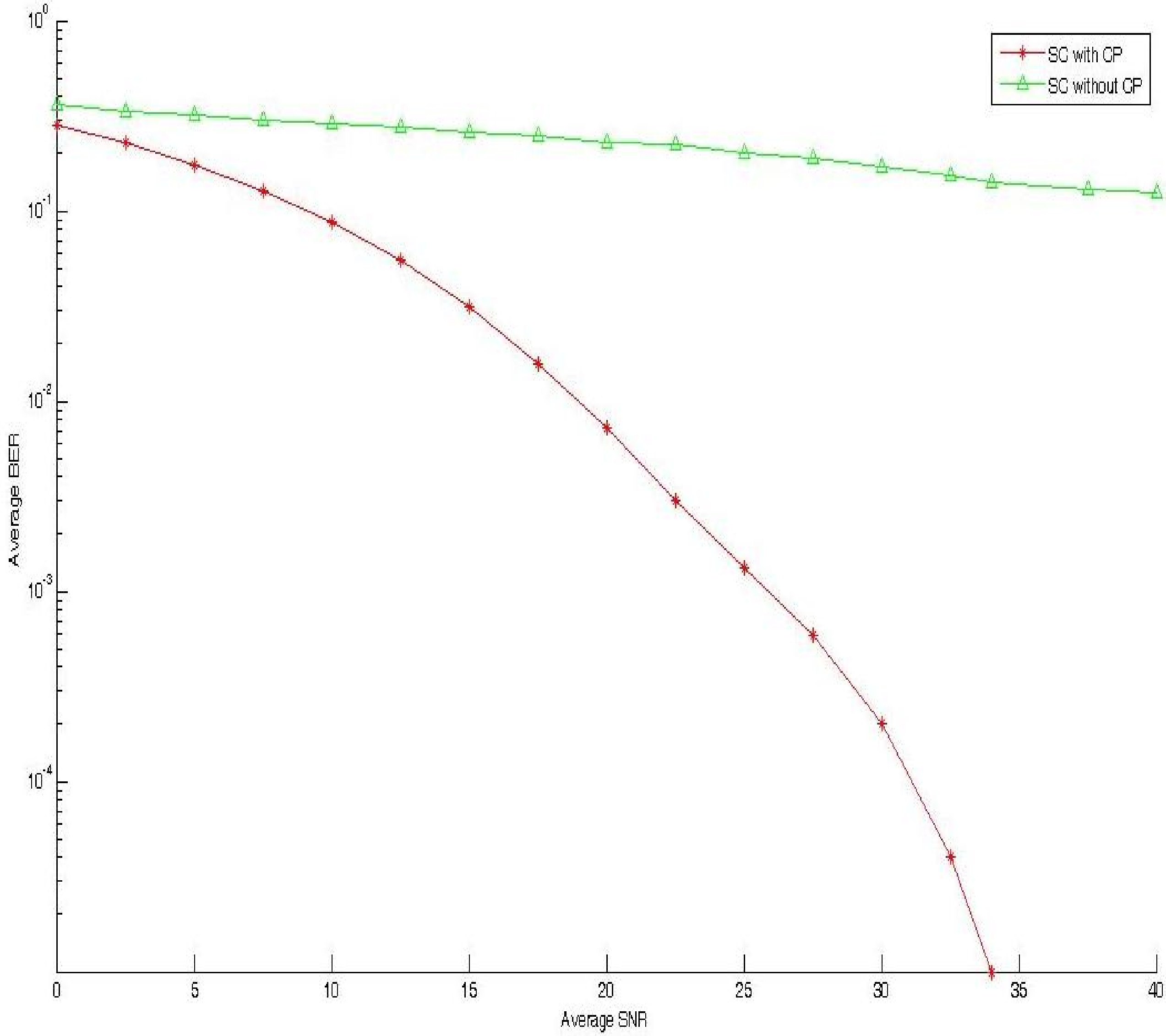


**Figure 6.7 Comparison curve between SC without Cyclic Prefix and SC with Cyclic Prefix for QPSK Modulation**

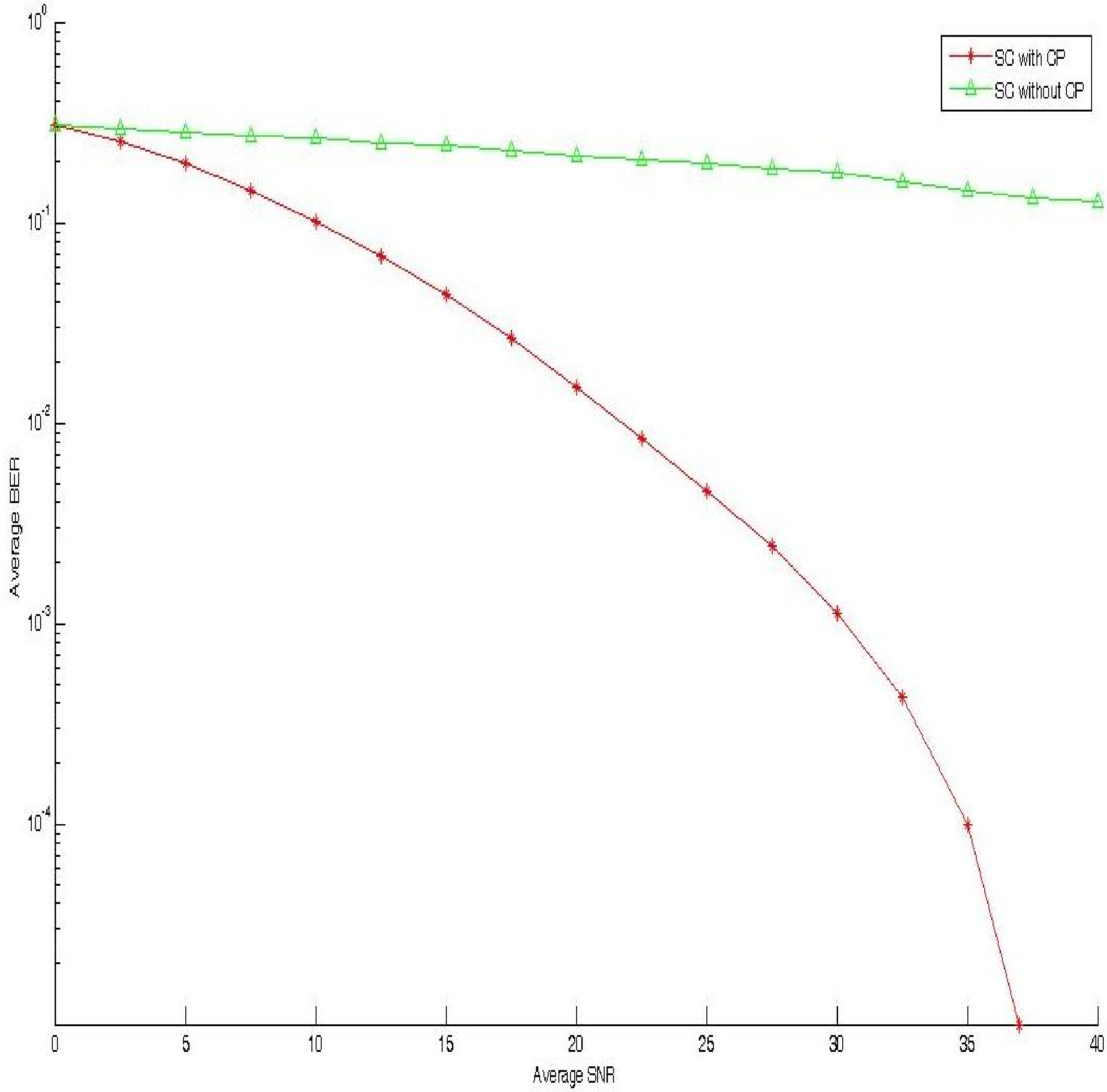


**Figure 6.8 Comparison curve between SC without Cyclic Prefix and SC with Cyclic Prefix for 16-QAM Modulation**

## 10.5 *Comparison of Convolution in Time Domain and Multiplication in Frequency*

**Time Domain convolution:**

- Filter time samples of receive window using Finite Impulse Response (FIR) filter
- Use transmit waveform samples as tap values (number of taps = TBP)

**Frequency domain complex multiplication:**

- FFT (of receive window)
- Complex multiplication by complex conjugate of FFT (transmit waveform)
- IFFT
- Overlap by TBP if sectioned convolution*

Both approaches mathematically equivalent

- Convolution (time) ⇔ multiplication (frequency)

Computational efficiency is the driving factor. Operations defined here as total number of multiplies and adds

Number of FIR operations per input sample:

$$= 8N - 2 \text{ where } N = \text{number of taps}$$

Number of FFT operations per input vector:

$$= 5\, N \log_2 N \text{ where } N = \text{FFT length}$$

**If TBW =256**

Both equations assume complex data

$$\text{FIR operations} = 8 * 256 - 2 = 2046$$

- 2046 operations need to happen every new input sample

FFT operations:

- Assume an FFT length of twice the TBP

$$5 * 512 * \log_2 (512) = 23,040$$

- This needs to happen twice (once for FFT, once for IFFT)*

$$= 2 * 23,040 = 46,080 \text{ operations}$$

- i.e. for every input vector, 46,080 operations need to occur
- Assuming sectioned convolution, overlap input vectors by TBP
- Thus, effective operations per input sample:

**46,080 / (512 – 256) = 180** operations per new input sample

FFT approach is over 11 times as efficient as FIR in this case!

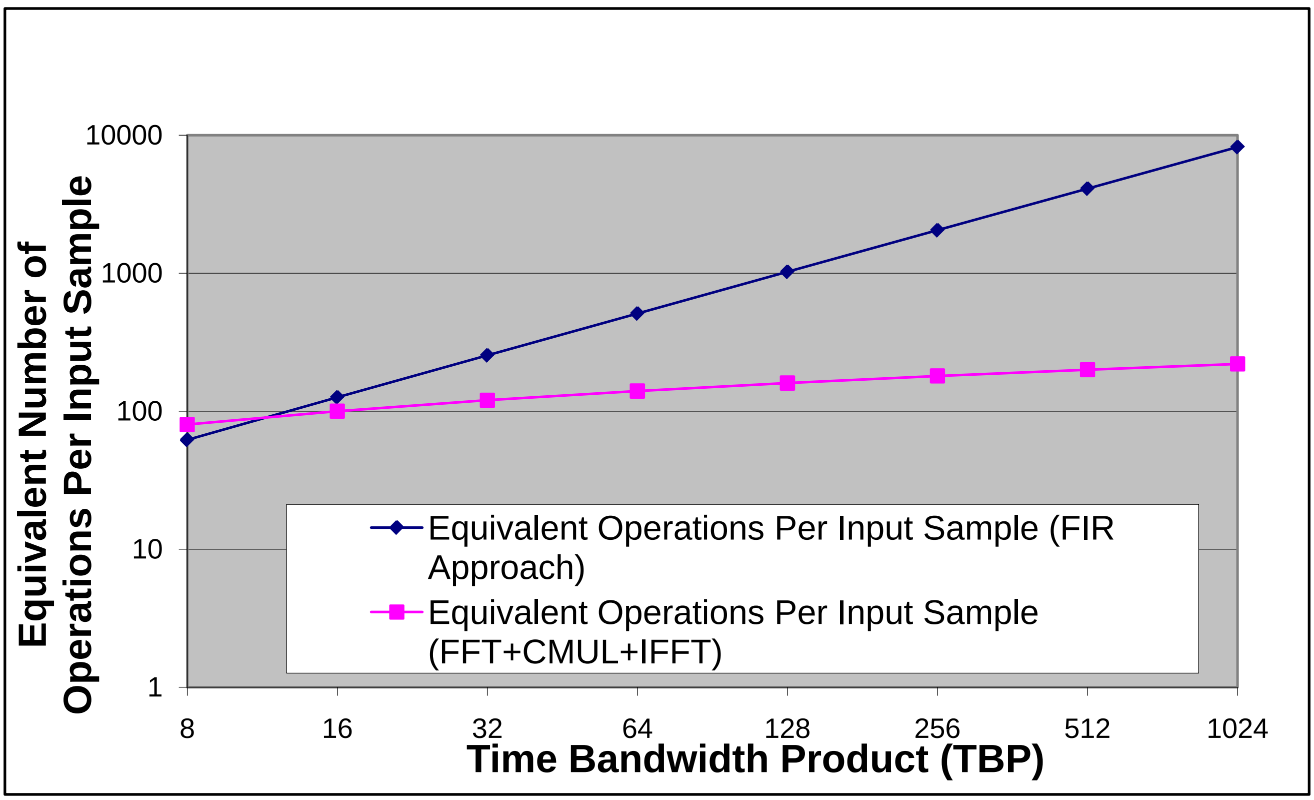


**Figure 6.9 Comparison curve between Convolution in Time Domain and Multiplication in Frequency Domain**

## 10.6 *Conclusion*

SCFDE with DFE has better performance as compared to SCFDE with DFE in Time Domain in prospective of Computational Complexity, processing time and has little better BER performance in dispersive channel environments.

SCFDE with FDE system is better than OFDM in some of the cases

- It has low PAPR.
- It is intolerant to nonlinearities of amplifier.
- It is less sensitive carrier frequency offsets.

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