Chapter 4
OFDM System with Novel Concatenated FEC schemes

4.1 Introduction
This chapter briefs the OFDM system model, implementation of FEC scheme-I in OFDM and implementation of scheme-II in OFDM and finally the simulation results.

4.2 The OFDM System Model
Efficient use of radio spectrum includes placing modulated carriers as close as possible without causing Inter-Carrier Interference (ICI). Optimally, the bandwidth of each carrier would be adjacent to its neighbors, so there would be no wasted spectrum. In practice, a guard band must be placed between each carrier bandwidth to provide a space where a filter can attenuate an adjacent carrier's signal. These guard bands are wasted bandwidth. In order to transmit high data rates, short symbol periods must be used. The symbol period is the inverse of the baseband data rate \( T = 1/R \), so as \( R \) increases, \( T \) must decrease. In a multi-path environment, a shorter symbol period leads to a greater chance for Inter-Symbol Interference (ISI). This occurs when a delayed version of symbol 'n' arrives during the processing period of symbol 'n+1'. Orthogonal Frequency Division Multiplexing (OFDM) addresses both of these problems. OFDM provides a technique allowing the bandwidths of modulated carriers to overlap without interference (no ICI). It also provides a high date rate with a long symbol duration, thus helping to eliminate ISI. OFDM may therefore be considered as a modulation technique in a broadband, multi-path environment. OFDM is a modulation technique [32],[43] where multiple low data rate carriers are combined by a transmitter to form a composite high data rate transmission. Digital signal processing makes OFDM possible. To implement the multiple carrier scheme using a bank of parallel modulators would not be very efficient in analog hardware. However, in the digital domain, multi-carrier modulation can be done efficiently with currently available DSP hardware and software. Not only can it be done, but it can also be made very flexible and programmable. This
allows OFDM to make maximum use of available bandwidth and to be able to adapt to changing system requirements. Each carrier in an OFDM system is a sinusoid with a frequency that is an integer multiple of a base or fundamental sinusoid frequency. Therefore, each carrier is like a Fourier series component of the composite signal. In fact, it will be shown later that an OFDM signal is created in the frequency domain, and then transformed into the time domain via the Discrete Fourier Transform (DFT). Two periodic signals are orthogonal when the integral of their product, over one period, is equal to zero.

OFDM can be simply defined as a form of multicarrier modulation where its carrier spacing is carefully selected so that each subcarrier is orthogonal to the other subcarriers. As it is well known that, orthogonal signals can be separated at the receiver by correlation techniques and hence intersymbol interference among channels can be eliminated. Orthogonality can be achieved by carefully selecting carrier spacing, such as letting the carrier spacing be equal to the reciprocal of the useful symbol period. In order to occupy sufficient bandwidth to gain advantages of the OFDM system, it would be good to group a number of users together to form a wideband system, in order to interleave data in time and frequency.

4.3 OFDM Generation

To generate OFDM [45] as shown in Figure 4.1 successfully, the relationship between all the carriers must be carefully controlled to maintain the orthogonality of the carriers. For this reason, OFDM is generated by first choosing the spectrum, based on the input data and modulation scheme. Each carrier to be produced is assigned some data to transmit. The required amplitude and phase of the carrier is then calculated based on the modulation scheme [46] (typically differential BPSK, QPSK, or QAM). The required spectrum is then converted back to its time domain signal using an Inverse Fourier Transform. The Inverse Fast Fourier Transform (IFFT) performs the transformation efficiently and provides a simple way of ensuring the carrier signals to be orthogonal.
The Fast Fourier Transform (FFT) transforms a cyclic time domain signal into its equivalent frequency spectrum. This is done by finding the equivalent waveform generated by a sum of orthogonal sinusoidal components. The amplitude and phase of the sinusoidal components represent the frequency spectrum of the time domain signal. The IFFT performs the reverse process, transforming a spectrum (amplitude and phase of each component) into a time domain signal. An IFFT converts a number of complex data points, of length that is a power of 2, into the time domain signal of the same number of points. Each data point in frequency spectrum used for an FFT or IFFT is called a bin.

The orthogonal carriers required for the OFDM signal can be easily generated by setting the amplitude and phase of each frequency bin, then performing the IFFT. Since each bin of an IFFT corresponds to the amplitude and phase of a set of orthogonal sinusoids, the reverse process guarantees that the carriers generated are orthogonal.

![Figure 4.1 OFDM Modulator](image-url)

The receiver in Figure 4.2 basically does the reverse operation to the transmitter. The guard period is removed. The FFT of each symbol is then taken to find the original transmitted spectrum. The phase angle of each transmission carrier is then evaluated and converted back to the data word by demodulating the received phase. The data words are then combined back to the same word size as the original data. It is an important part of the OFDM system design that the bandwidth occupied is greater than the correlation bandwidth of the fading channel. A good understanding of the propagation statistics is needed to ensure
that this condition is met. Then, although some of the carriers are degraded by multipath fading, the majority of the carriers should still be adequately received. OFDM can effectively randomize burst errors caused by Rayleigh fading, which comes from interleaving due to parallelization. So, instead of several adjacent symbols being completely destroyed, many symbols are only slightly distorted.

![Figure 4.2 OFDM Demodulator](image)

**The Importance of Orthogonality**

The "orthogonal" part of the OFDM name indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal FDM system, the many carriers are spaced apart in such way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands have to be introduced between the different carriers as shown in Figure 4.3 and the introduction of these guard bands in the frequency domain results in a lowering of the spectrum efficiency. It is possible, however, to arrange the carriers in an OFDM [64] signal so that the sidebands of the individual carriers overlap and the signals can still be received without adjacent carrier interference. In order to do this the carriers must be mathematically
orthogonal. The receiver acts as a bank of demodulators, translating each carrier down to DC, the resulting signal then being integrated over a symbol period to recover the raw data. If the other carriers all beat down in the symbol period \((t)\), then the integration process results in zero contribution from all these carriers. Thus the carriers are linearly independent (i.e. orthogonal) if the carrier spacing is a multiple of \(1/t\). Mathematically, suppose if there is a set of signals \(y\), where \(y(p)\) is the \(p^{th}\) element in the set and then

\[
\int_{a}^{b} \psi_p(t)\psi^*_q(t)dt = \begin{cases} K & \text{for } p = q \\ 0 & \text{for } p \neq q \end{cases} 
\]

(4.1a)

where the * indicates the complex conjugate and interval \([a, b]\) is a symbol period. A fairly simple mathematical proof exists, that the series \(\sin(mx)\) for \(m=1, 2\), are orthogonal over the interval \(-\pi\) to \(\pi\).

![Conventional FDM technique](image)

**Conventional FDM technique**

![OFDM modulation technique](image)

**OFDM modulation technique**

**Figure 4.3 Comparison of the bandwidth utilization for FDM and OFDM**
Mathematical Description of OFDM

OFDM transmits a large number of narrowband carriers closely spaced in the frequency domain as shown in Figure 4.4. In order to avoid a large number of modulators and filters at the transmitter and complementary filters and demodulators at the receiver, it is desirable to be able to use modern digital signal processing techniques, such as Fast Fourier Transform (FFT).

Mathematically, each carrier can be described as a complex wave:

\[ S_c(t) = A_c(t)e^{j(\omega_0 t + \Phi_c(t))} \]  

\[ S_s(kT) = \frac{1}{N} \sum_{n=0}^{N-1} A_n(t)e^{j(\omega_0 t + \phi_n(t))} \]  

where \( \omega_n = \omega_0 + n \Delta \omega \) , \( n \)-th carrier of frequency \( f_n = f_0 + n\Delta f \)

Figure 4.4 OFDM spectrum (a) a single sub channel, (b) 5 carriers at the central frequency of each sub channel, there is no crosstalk from other sub channels.
Considering the waveforms of each component of the signal over one symbol period, the variables $A_c(t)$ and $f_c(t)$ take on fixed values, which depend on the frequency of that particular carrier, and so can be rewritten as

$$
\phi_n(t) \Rightarrow \phi_n \\
A_n(t) \Rightarrow A_n
$$

(4.2b)

If the signal is sampled using a sampling frequency of $1/T$, then the resulting signal is represented by

$$
S_s(kT) = \frac{1}{N} \sum_{n=0}^{N-1} A_n e^{j[(na_n+n\Delta\omega)kT+\Phi_n]}
$$

(4.3)

At this point, it is restricted that the time over which the signal is analyzed to $N$ samples. It is convenient to sample over the period of one data symbol. Thus it gives a relationship: $\tau = NT$

If (4.3) is simplified, without a loss of generality by letting $w_0=0$, then the signal becomes

$$
S_s(kT) = \frac{1}{N} \sum_{n=0}^{N-1} A_n e^{j\phi_n} e^{j(n\Delta\omega)kT}
$$

(4.4)

Now (4.4) by letting $w_0=0$, without the loss of general form of the inverse Fourier transform

$$
g(kT) = \frac{1}{N} \sum_{n=0}^{N-1} G(n) e^{j2\pi mk/N}
$$

(4.5)

In (4.4), the function $A_n e^{j\phi_n}$ is no more than a definition of the signal in the sampled frequency domain, and $S(kT)$ is the time domain representation (4.4) and (4.5) are equivalent if

$$
\Delta f = \frac{\Delta \omega}{2\pi} = \frac{1}{NT} = \frac{1}{\tau}
$$

(4.6)
This is the same condition that was required for orthogonality. Thus, one consequence of maintaining orthogonality is that the OFDM signal can be defined by using Fourier transform procedures.

**Need of the FFT in OFDM**

At the transmitter, the signal is defined in the frequency domain. It is a sampled digital signal, and it is defined such that the discrete Fourier spectrum exists only at discrete frequencies. Each OFDM carrier corresponds to one element of this discrete Fourier spectrum. The amplitudes and phases of the carriers depend on the data to be transmitted. The data transitions are synchronized at the carriers, and can be processed together symbol by symbol.

The definition of the (N-point) discrete Fourier transform is given as

\[ X_p[k] = \sum_{n=0}^{N-1} x_p[n] e^{-j(2\pi/N)kn} \]  

(4.7)

and the (N-point) inverse discrete Fourier transform (IDFT) is

\[ X_p[n] = \frac{1}{N} \sum_{k=0}^{N-1} X_p[k] e^{j(2\pi/N)kn} \]  

(4.8)

A natural consequence of this method is that it allows us to generate carriers that are orthogonal. The members of an orthogonal set are linearly independent. Consider a data sequence \((d_0, d_1, d_2, \ldots, d_{N-1})\), where each \(d_n\) is a complex number 
\(d=a_n+jb_n\).

\((a_n, b_n=\pm1\) for QPSK, \(a_n, b_n=\pm1, \pm3\) for 16QAM)  

\[ D_m = \sum_{n=0}^{N-1} d_n e^{-j(2\pi f_m n)} \]  

(4.9)

where \(f_m=n/ (N D_t)\), \(D_t\) is an arbitrarily chosen symbol duration of the serial data sequence \(d_n\). Hence \(t_k=k D_t\). The real part of the vector \(D\) has components
\[ Y_m = \text{Re} \{ D_m \} = \sum_{n=0}^{N-1} [(a_n \cos (2\pi f_n t_m) + b_n \sin (2\pi f_n t_m))] \quad k=0, 1, 2 \ldots N-1 \quad (4.10) \]

If these components are applied to a low-pass filter at time intervals \( D_t \), a signal is obtained that closely approximates the frequency division multiplexed signal

\[ y(t) = \sum_{n=0}^{N-1} [(a_n \cos (2\pi f_n t_m) + b_n \sin (2\pi f_n t_m))] \quad 0 < t < N \Delta t \quad (4.11) \]

The incoming serial data is first converted from serial to parallel and grouped into \( x \) bits each to form a complex number. The number \( x \) determines the signal constellation of the corresponding subcarrier, such as 16 QAM or 32QAM. The complex numbers are modulated in the baseband by the inverse FFT (IFFT) and converted back to serial data for transmission. A guard interval is inserted between symbols to avoid intersymbol interference (ISI) caused by multipath distortion. The discrete symbols are converted to analog and low-pass filtered for RF up conversion. The receiver performs the inverse process of the transmitter. One-tap equalizer is used to correct channel distortion. The tap-coefficients of the filter are calculated based on the channel information.

![Figure 4.5 Example of the power spectral density of the OFDM signal with a guard interval \( D = T_s/4 \) (number of carriers \( N=32 \))](image-url)
Figure 4.6 presents composite OFDM spectrum 512 samples by MATLAB simulation. By carefully selecting the carrier spacing, the OFDM signal spectrum can be made flat and the orthogonality among the sub channels can be guaranteed.

4.4 Channel Model for OFDM Performance

Four main criteria were used to assess the performance of the OFDM system. They are i) tolerance to multipath delay spread, ii) channel noise, iii) peak power clipping and iv) time synchronization errors. An OFDM system was modelled using Matlab to allow various parameters of the system to be varied and tested. The channel model is now considered to the transmitted signal. The signal to noise ratio is set by adding a known amount of white noise to the transmitted signal. Multipath delay spread is then added by simulating the delay spread using an FIR filter. The length of the FIR filter represents the maximum delay spread, while the coefficient amplitude represents the reflected signal magnitude. The aim was to develop a mathematical model of the BER performance of OFDM versus the channel noise. This was so developed that the
simulated results could be verified, and to get a more in depth understanding of the transmission mechanism.

**RMS Demodulated Phase Error**

In IQ diagram of the transmitted signal, the transmitted signal has a fixed magnitude and phase corresponding to the data to be transmitted as shown in Figure 4.7.

![Figure 4.7 IQ Diagram of QPSK](image)

The noise can then be considered as the random vector added to the transmitted signal shown in Figure 4.8. The magnitude of the phase error depends on two factors namely, the relative phase angle of the noise vector and

![Figure 4.8 IQ diagram with random noise](image)
the magnitude of the noise vector. The received vector will be the vector sum of the transmitted signal and the noise. It is assumed that the noise is a constant magnitude vector equal to its RMS magnitude, and that it has a random phase angle then the problem of working out the received angle would be as follows.

**Performance Degradation of OFDM Due to Channel Noise**

Figure 4.3 shows the effect of noise on the received phase angle. Let the amplitude of the transmitted signal be 1, and the length of the noise vector be A with angle \( \varphi \), then the received phase error is \( \theta_{\text{err}} \). Figure 4.9 shows effect of noise on the received phase angle.

![Figure 4.9 Received Phasor](image)

The noise signal can be of any phase angle. To find the RMS phase error, find the average phase error (assuming the noise phase angle is always positive) then this can be scaled to find the RMS error. The average phase angle can be found by integrating \( \theta_{\text{err}} \) over a half circle, i.e. \( \varphi \) varies from 0 to \( \pi \)

\[
\text{Average } \theta_{\text{err}} = \frac{1}{\pi} \int_{0}^{\pi} \tan^{-1} \left( \frac{\sin \varphi}{SNR + \cos \varphi} \right) d\varphi
\]

The RMS phase error will be greater by root 2, thus

\[
\text{RMS } \theta_{\text{err}} = \frac{\sqrt{2}}{\pi} \int_{0}^{\pi} \tan^{-1} \left( \frac{\sin \varphi}{SNR + \cos \varphi} \right) d\varphi
\]  

(4.12)

**Uniform noise**

AWGN is the most common impairment encountered in a communications system. The effect of AWGN on an OFDM system is similar to its effect on a single carrier system. The signal-to noise ratio (SNR) is a function of the total signal power over the total noise power across the received channel. The uniform
noise contributes to the SNR of each subcarrier in the OFDM system and the net result is equivalent to the effect on single channel systems.

**Impulse noise**

Impulse noise is a common impairment in a communications system arising from motors or lightning. Impulse noise is typically characterized as a short time-domain burst of energy. The burst may be repetitive or may be a single event. In either case, the frequency spectrum from this energy burst is wideband, typically much wider than the channel, but is present for only a short time period. OFDM takes symbols and creates these groups directly and then transforms them. They are no longer time-domain multiplexed; they are now frequency-domain multiplexed. The OFDM symbol is now a collection of these source symbols, and this OFDM symbol now has a much longer duration. Each original symbol occupies only a small frequency region, but now occupies that region for the entire OFDM symbol duration. For impulses that are short in duration, the impulse energy masks a smaller percentage of time of each OFDM symbol compared to the single carrier case.

**Carrier interference**

Single-carrier interference arises from other sources that may co-exist in the frequency range of interest. These can be generated by nearby circuits or other transmission sources. The single carrier system must handle this interference as a noise source for all information sent. The OFDM system can avoid the frequency region of interference by disabling or turning off the affected subcarriers. Narrowband modulated sources of interference can be considered similar to carrier interference in their impairment.

Due to above noises, the performance degradation is there in OFDM. Hence it is required to increase its performance. So there is a need of efficient FEC schemes for error correction.
4.5 Implementation of the Novel Concatenated FEC Scheme-I in OFDM System

The distribution of the data over many carriers means that selective fading will cause some bits to be received with error while others are received correctly. Apart from many issues in the system, the channel also adds its own noise components as discussed in chapter 1. By using an error-correcting code which adds extra bits at the transmitter, it is possible to correct many or all of the bits that were incorrectly received. The OFDM system performance can be increased by employing FEC recommended for its use in OFDM system. To improve the system performance still, the only solution required is that implementing the proposed a novel FEC scheme by Concatenation of RS code and Irregular Turbo [79] [80] [84] code in OFDM system as shown in Figure 4.10

![Figure 4.10 a Novel FEC scheme-I for OFDM system](image-url)
Design Steps for the Implementation

- A sequence of random input bits is generated
- The input data is converted into symbols of the Galois Field GF(2^5)
- These symbols should be divided into frames. These frames are given to the Reed-Solomon coder (Outer Coder).
- Each block of symbols is encoded using RS encoding process
- RS coded symbols of field GF(2^5) are converted back into bits
- These bits are divided into blocks and then fed to Irregular Turbo coder (Inner Coder)
- These bits are then encoded by Irregular Turbo coding method.
- These encoded bits are given to OFDM transmitter.
- Here bits are modulated in QPSK modulation and given over noisy channel like AWGN or Rayleigh channel. These channels add noise components with its input signal. From this noisy channel, the signal is given to the OFDM receiver section.
- The received bits are demodulated in QPSK demodulator of OFDM receiver. Those bits are having now error bits. These error bits are to be corrected by this proposed scheme.
- The demodulated noisy bits are fed to Irregular decoder (Inner Decoder) which involves iterative decoding. The decoding operation should be repeated for specific number of iterations.
- The signal now is despread by the code employed at the transmitter.
- These bits are divided into blocks and are converted back to symbols of GF (2^5). Then these symbols are fed to RS decoder
- The symbols are decoded by RS decoder and then again output symbols are converted back to bits and these bits are given to comparator.

The comparator will compare decoded bits with original bits to compute bit error rate. The delay in the Figure 4.10 is kept because there will be some delay for encoding and decoding.
Simulation Results

The performance of concatenated RS and Irregular Turbo codes are analyzed using data frame sizes of 460, which is close to the GSM standard (456 bits) for both AWGN and Rayleigh channels. All the simulations are performed using MATLAB.

### Table 4.1 Specifications of RS code in OFDM

<table>
<thead>
<tr>
<th>RS code parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field used</td>
<td>GF ($2^5$)</td>
</tr>
<tr>
<td>Message length (k)</td>
<td>31</td>
</tr>
<tr>
<td>Encoded length (n)</td>
<td>23</td>
</tr>
<tr>
<td>Error correcting capability (t)</td>
<td>4 symbols</td>
</tr>
<tr>
<td>Generator polynomial (g)</td>
<td>[5 30 9 1 19 23 22 3 0]</td>
</tr>
<tr>
<td>Encoding type</td>
<td>Systematic</td>
</tr>
<tr>
<td>Name of Iterative algorithm</td>
<td>Berlekemp's iterative algorithm</td>
</tr>
<tr>
<td>Error magnitudes computation</td>
<td>Forney algorithm</td>
</tr>
<tr>
<td>Roots finding in GF</td>
<td>Chein's search algorithm</td>
</tr>
</tbody>
</table>

### Table 4.2 Specifications of Irregular Turbo code in OFDM

<table>
<thead>
<tr>
<th>Irregular Turbo code parameters</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator polynomial type</td>
<td>RSC</td>
</tr>
<tr>
<td>Feed back Generator polynomial</td>
<td>$[1 1 1]_2$ or $7_8$</td>
</tr>
<tr>
<td>Feed forward Generator polynomial</td>
<td>$[1 0 1]_2$ or $5_8$</td>
</tr>
<tr>
<td>Irregularity type</td>
<td>pseudo-random</td>
</tr>
<tr>
<td>Irregularity percentage</td>
<td>10 %</td>
</tr>
<tr>
<td>Interleaver Type</td>
<td>Golden</td>
</tr>
<tr>
<td>Interleaver size</td>
<td>460</td>
</tr>
<tr>
<td>Decoding algorithm</td>
<td>Log-MAP</td>
</tr>
<tr>
<td>Decoding iterations</td>
<td>3</td>
</tr>
</tbody>
</table>
Table 4.3 Specifications of Turbo code in OFDM

<table>
<thead>
<tr>
<th>Turbo code parameters</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frame size</td>
<td>460 bits</td>
</tr>
<tr>
<td>Number of frame repetitions</td>
<td>1000</td>
</tr>
<tr>
<td>Generator polynomial type</td>
<td>RSC</td>
</tr>
<tr>
<td>Feed back Generator polynomial</td>
<td>([1 1 1]_2 \text{ or } 7_b)</td>
</tr>
<tr>
<td>Feed forward Generator polynomial</td>
<td>([1 0 1]_2 \text{ or } 5_b)</td>
</tr>
<tr>
<td>Puncturing</td>
<td>Unpunctured</td>
</tr>
<tr>
<td>Interleaver Type</td>
<td>Golden</td>
</tr>
<tr>
<td>Interleaver size</td>
<td>460</td>
</tr>
<tr>
<td>Rate</td>
<td>unpunctured (1/3)</td>
</tr>
<tr>
<td>Decoding algorithm</td>
<td>Log-MAP</td>
</tr>
<tr>
<td>Number of decoding iterations</td>
<td>3</td>
</tr>
<tr>
<td>Field used</td>
<td>GF ((2^5))</td>
</tr>
<tr>
<td>Message length ((k))</td>
<td>23</td>
</tr>
<tr>
<td>Encoded length ((n))</td>
<td>31</td>
</tr>
<tr>
<td>Error correcting capability ((t))</td>
<td>4 symbols</td>
</tr>
<tr>
<td>Channels</td>
<td>AWGN and Rayleigh</td>
</tr>
<tr>
<td>Irregularity type</td>
<td>pseudo-random</td>
</tr>
<tr>
<td>Irregularity percentage</td>
<td>5%, 10% and 15%</td>
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<tr>
<td>Interleaver in Irregular Turbo code</td>
<td>Golden</td>
</tr>
<tr>
<td>Decoding algorithm in Irregular Turbo code</td>
<td>Log-Map.</td>
</tr>
</tbody>
</table>

Figure 4.11. shows the BER of OFDM system with individual RS and Irregular Turbo code in AWGN Channel. The BERs of RS code alone implemented in OFDM at 5 dB, 10dB and 15dB are \(6 \times 10^{-2}, 9 \times 10^{-3}\), and \(15 \times 10^{-4}\) respectively by simulation. At 5 dB, 10dB and 15dB, BERs of OFDM with Irregular Turbo alone are \(4 \times 10^{-2}, 5 \times 10^{-3}\) and \(9 \times 10^{-4}\) respectively in this simulation. These values are tabulated in Table 4.4
Figure 4.11 BER performance of OFDM system with RS code alone and Irregular code alone in AWGN Channel

Table 4.4 BER performance of OFDM system with RS code alone and Irregular code alone in AWGN Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RS</td>
<td>6 X10^{-2}</td>
<td>9 X10^{-3}</td>
<td>15X10^{-2}</td>
</tr>
<tr>
<td>2</td>
<td>Irregular Turbo</td>
<td>4 X10^{-2}</td>
<td>5 X10^{-3}</td>
<td>9X10^{-4}</td>
</tr>
</tbody>
</table>

Figure 4.12 shows BER of OFDM system with proposed concatenated FEC scheme-I on AWGN Channel. The BERs of concatenated RS code and Turbo code [48] at 5dB, 10dB and 15dB are 2.5 X10^{-2}, 3.5 X10^{-3} and 5 X10^{-4} respectively. The BERs of proposed concatenated RS code and Irregular Turbo code (10%) on OFDM system [78] [79] [83] simulated as per above parameters at 5dB, 10dB and 15dB are 1.5 X10^{-2}, 2.5 X10^{-3} and 3.5 X10^{-4} respectively. These values are tabulated in Table 4.5.
Figure 4.12  BER performance of OFDM System with concatenated RS code and Irregular code in AWGN Channel

Table 4.5  BER performance of OFDM System with concatenated RS code and Irregular code in AWGN Channel

<table>
<thead>
<tr>
<th>S. No.</th>
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<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RS &amp; Turbo</td>
<td>2.5X10^{-2}</td>
<td>3.5X10^{-3}</td>
<td>5X10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>RS &amp; Irregular Turbo (5%)</td>
<td>2X10^{-2}</td>
<td>3X10^{-3}</td>
<td>4X10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>RS &amp; Irregular Turbo (10%)</td>
<td>1.5X10^{-2}</td>
<td>2.5X10^{-3}</td>
<td>3.5X10^{-4}</td>
</tr>
<tr>
<td>4</td>
<td>RS &amp; Irregular Turbo (15%)</td>
<td>1X10^{-2}</td>
<td>1.5X10^{-3}</td>
<td>3X10^{-4}</td>
</tr>
</tbody>
</table>

Figure 4.13 shows BER of OFDM systems with individual RS and Irregular turbo Code considered on Rayleigh Channel. The BERs of RS code alone implemented in OFDM at 5 dB, 10dB and 15dB are 20X10^{-2}, 6X10^{-2} and 2.5X10^{-2} respectively. At 5 dB, 10dB and 15dB, BERs of OFDM with Irregular Turbo alone
[75] are $10 \times 10^{-2}$, $4 \times 10^{-2}$ and $1.5 \times 10^{-2}$ respectively. These values are tabulated in table in Table 4.6.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RS</td>
<td>$20 \times 10^{-2}$</td>
<td>$6 \times 10^{-2}$</td>
<td>$2.5 \times 10^{-2}$</td>
</tr>
<tr>
<td>2</td>
<td>Irregular Turbo</td>
<td>$10 \times 10^{-2}$</td>
<td>$4 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Figure 4.13 BER performance of OFDM system with RS code alone and Irregular Turbo code alone in Rayleigh Channel

Table 4.6 BER performance of OFDM system with RS code alone and Irregular Turbo code alone in Rayleigh Channel

Figure.14 shows BER of OFDM system with proposed concatenated FEC on Rayleigh Channel. The BER of OFDM system with both RS code and Turbo code implemented are equal to $6.5 \times 10^{-2}$, $2 \times 10^{-2}$ and $7 \times 10^{-3}$ at 5dB, 10dB and 15dB respectively. The BERs of concatenated RS code and Irregular Turbo code (10%) on OFDM system [84] as per above parameters at 5dB, 10dB and 15dB are $4 \times 10^{-2}$, $1.3 \times 10^{-2}$ and $4.5 \times 10^{-3}$ respectively.
Figure 4.14  BER performance of OFDM System with concatenated RS code and Irregular code in Rayleigh Channel

Table 4.7 BER performance of OFDM System with concatenated RS code and Irregular code in Rayleigh Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=14dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>RS &amp; Turbo</td>
<td>6.5 $\times 10^{-2}$</td>
<td>2 $\times 10^{-2}$</td>
<td>7 $\times 10^{-3}$</td>
</tr>
<tr>
<td>2</td>
<td>RS &amp; Irregular Turbo (5%)</td>
<td>5.5 $\times 10^{-2}$</td>
<td>1.6 $\times 10^{-2}$</td>
<td>5.5 $\times 10^{-3}$</td>
</tr>
<tr>
<td>3</td>
<td>RS &amp; Irregular Turbo (10%)</td>
<td>4 $\times 10^{-2}$</td>
<td>1.3 $\times 10^{-2}$</td>
<td>4.5 $\times 10^{-3}$</td>
</tr>
<tr>
<td>4</td>
<td>RS &amp; Irregular Turbo (15%)</td>
<td>3 $\times 10^{-2}$</td>
<td>9.5 $\times 10^{-3}$</td>
<td>3.5 $\times 10^{-3}$</td>
</tr>
</tbody>
</table>
4.6 Implementing the Novel Concatenated FEC scheme-II in OFDM system

OFDM performance can be still increased by employing another concatenated scheme using Turbo and Irregular Turbo codes as shown in Figure 4.15. They are latest codes and of the same nature. These codes are already dealt in the section 3.3.

Design steps for the Implementation

- A sequence of random input bits is generated.
- The input data is converted into symbols of the Galois field GF (2^5).
- These bits are divided into blocks and fed to Turbo coder (Outer Coder).
- These bits are then encoded by Irregular Turbo coder.
- These encoded bits are given to OFDM transmitter, where they are modulated using QPSK modulation.
- Then they are subjected to noisy channel like AWGN or Rayleigh channel. These channels add noise components with its input signal. From this noisy channel, the signal is given to the receiver OFDM receiver section.
- The received bits are demodulated in QPSK demodulator of OFDM receiver. The error bits present in the received bits are to be corrected by the proposed error correcting scheme.
- The demodulated noisy bits are fed to Irregular Turbo decoder (inner decoder) which involves iterative decoding. The decoding operation should be repeated for specific number of iterations for the bit error rate $10^{-6}$.
- The Irregular Turbo decoded data bits are given to Turbo decoder (Outer Decoder) and these bits are given to comparator
- The comparator will compare decoded bits with original bits to compute bit error rate.
When Turbo code alone is implemented in OFDM, the BERs at 5 dB, 10 dB and 15 dB are $5 \times 10^{-2}$, $7 \times 10^{-3}$, and $1 \times 10^{-3}$ respectively. At 5 dB, 10 dB, and 15 dB BERs of OFDM with Irregular Turbo (10%) alone are $4 \times 10^{-2}$, $6 \times 10^{-3}$, and $9 \times 10^{-4}$ respectively. These values are tabulated in Table 4.8.
OFDM BER Vs SNR in AWGN Channel

10

OFDM with Turbo code alone
OFDM with Ir. Turbo code(10%) alone

10

Figure 4.16 BER performance of OFDM system with Turbo code alone and
Irregular code alone in AWGN Channel

Table 4.8 BER performance of OFDM system with Turbo code alone and Irregular
Turbo code alone in AWGN Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbo code</td>
<td>5 X10^-2</td>
<td>7 X10^-3</td>
<td>1 X10^-3</td>
</tr>
<tr>
<td>2</td>
<td>Irregular Turbo</td>
<td>4 X10^-2</td>
<td>6 X10^-3</td>
<td>9 X10^-4</td>
</tr>
</tbody>
</table>

Figure 4.17 shows BER performance of OFDM system with proposed
Concatenated FEC-II on AWGN Channel. The BERs of concatenated Turbo
code and Irregular Turbo code (10%) performance on OFDM system simulated
as per above parameters are 1.5 X10^-2, 2 X10^-3 and 3 X10^-4 at 5dB,10dB and
14dB respectively. The BERs of concatenated Turbo code and Irregular Turbo
code (15%) performance on OFDM system simulated as per above parameters
are $1.2 \times 10^{-2}$, $1.5 \times 10^{-3}$ and $2 \times 10^{-4}$ at 5dB, 10dB and 15dB respectively. The
same are tabulated in Table 4.9.

Figure 4.17 BER performance of OFDM System with concatenated Turbo code and
Irregular Turbo code in AWGN Channel

Table 4.9 BER performance of OFDM System with concatenated Turbo code and
Irregular Turbo code in AWGN Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbo &amp; Irr. Turbo (5%)</td>
<td>$2 \times 10^{-2}$</td>
<td>$2.5 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>Turbo &amp; Irr. Turbo (10%)</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>Turbo &amp; Irr. Turbo (15%)</td>
<td>$1.2 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-3}$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Figure 4.18 shows BER of OFDM systems performance on Rayleigh Channel. With Turbo code alone, the BERs in OFDM at 5 dB, 10dB and 15dB are $1.5 \times 10^{-1}$.
At 5 dB, 10 dB and 15 dB, BERs of OFDM with Irregular Turbo (10%) alone are $1 \times 10^{-1}$, $4 \times 10^{-2}$ and $0.5 \times 10^{-2}$ respectively. The same are tabulated in Table 4.10.

**Figure 4.18** BER performance of OFDM system with Turbo code alone and Irregular Turbo code alone in Rayleigh Channel

**Table 4.10** BER performance of OFDM system with Turbo code alone and Irregular Turbo code alone in Rayleigh Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbo</td>
<td>$1.5 \times 10^{-1}$</td>
<td>$5 \times 10^{-2}$</td>
<td>$1.9 \times 10^{-2}$</td>
</tr>
<tr>
<td>2</td>
<td>Irregular Turbo</td>
<td>$1 \times 10^{-1}$</td>
<td>$4 \times 10^{-2}$</td>
<td>$1.5 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

Figure 4.19 shows BER performance of OFDM system with proposed Concatenated FEC on AWGN Channel. The BERs of concatenated Turbo code and Irregular Turbo code (10%) performance on OFDM system simulated as per above parameters are $1.5 \times 10^{-2}$, $3 \times 10^{-3}$ and $7 \times 10^{-4}$ at 5 dB, 10 dB and 15 dB respectively. The BERs of concatenated Turbo code and Irregular Turbo code (15%) performance on OFDM system simulated as per above parameters are
$1 \times 10^{-2}$, $2 \times 10^{-3}$ and $3.5 \times 10^{-4}$ at 5dB, 10dB and 15dB respectively. The same are tabulated in Table 4.11.

![OFDM BER Vs SNR in Rayleigh Channel](image)

**Figure 4.19** BER performance of OFDM System with concatenated Turbo code and Irregular Turbo code in Rayleigh Channel

**Table 4.11** BER performance of OFDM System with concatenated Turbo code and Irregular Turbo code in Rayleigh Channel

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Code</th>
<th>BER at SNR=5dB</th>
<th>BER at SNR=10dB</th>
<th>BER at SNR=15dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Turbo &amp; Irr. Turbo (5%)</td>
<td>$2 \times 10^{-2}$</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$7 \times 10^{-4}$</td>
</tr>
<tr>
<td>2</td>
<td>Turbo &amp; Irr. Turbo (10%)</td>
<td>$1.5 \times 10^{-2}$</td>
<td>$3 \times 10^{-3}$</td>
<td>$5 \times 10^{-4}$</td>
</tr>
<tr>
<td>3</td>
<td>Turbo &amp; Irr. Turbo (15%)</td>
<td>$1 \times 10^{-2}$</td>
<td>$2 \times 10^{-3}$</td>
<td>$3.5 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The CDMA system and OFDM are combined to yield the advantages of both systems. The next chapter discusses the CDMA-OFDM system with these proposed error correction techniques and its error performance.