CHAPTER 3

A TECHNIQUE FOR ICI CANCELLATION USING BAYESIAN PROBABILITY AND PARALLEL CANCELLATION (BPICI)

3.1 INTRODUCTION

Bayesian Probability based Intercarrier Interference Cancellation techniques is proposed in this research work. The technique employs Bayesian probability computation process and parallel cancellation. The transmitted signals propagate through the channel and are received by receiver. In the receiver, hard decision decoding on spatial dimension is carried out and subsequently, parallel cancelation is carried out. It is improved by the use of Bayesian probability.

3.2 CONTRIBUTIONS OF THE PROPOSED TECHNIQUE

The work discusses MIMO-OFDM system using Bayesian probability based intercarrier interference cancellation technique. Both the Rayleigh and Rician fading channels are considered independently. BER curves are plotted for the evaluation purpose. Various curves are obtained by varying the fading channel, number of user signals and number of antennas. BER curves are drawn for proposed BPICI, PIC and MVDR.
3.3 PROPOSED BPICI CANCELLER

Parallel interference canceller is proposed for MIMO-OFDM based wireless communication systems using Bayesian probability computation process and parallel cancellation. MIMO systems have more than one input and more than one output. In orthogonal frequency division multiplexing, digital data are encoded on multiple carrier frequencies. The signals are transmitted by the antenna array set which propagates through the channel and are received by the receiver antenna array after travelling through the channel. When the signal is propagated through the channel, channel noise (Rayleigh channel noise) and the white gaussian noise are added to the signals. In the receiver, hard decision decoding on spatial dimension is carried out and subsequently, Bayesian probability is employed to complete the proposed Bayesian probability based intercarrier interference cancellation technique. The block diagram of the proposed technique is given in Figure 3.1.

![Block diagram of the proposed BPICI technique](image)

Figure 3.1 Block diagram of the proposed BPICI technique

In the transmitter section, the input data is initially orthogonal frequency division multiplexed then, QPSK modulated, then taken inverse FFT and finally transmitted through the antenna arrays. Consider there are
\( N \) signals in the user input serial signal data and let it be represented as \( G \) which is defined by Equation (3.1):

\[
G = (g_1, g_2, \ldots, g_N)^T \quad (3.1)
\]

The serial data is then split into parallel data streams or channels using orthogonal frequency division multiplexing. OFDM has the benefit that it has the ability to eliminate interference ISI and also achieves higher diversity gain and signal-to-noise ratio. The serial data \( G \) is converted into \( K \) number of parallel data streams. Let each parallel data stream be represented as \( G_i \) (where \( 0 < i \leq K \)) and \( G_i \) would contain defined number of data bits from the input stream \( g_i \) (where \( 0 < i \leq N \)), which means \( \{g_i\} \subseteq G \).

The operation can be mathematically noted as:

\[
G = (G_1, G_2, \ldots, G_K)^T \quad (3.2)
\]

For this procedure, a serial to parallel converter is employed and parallel streams of data is obtained. Subsequently, each sub-carrier is modulated with quadrature phase shift keying which is a type of bandwidth preserving modulation method. Here, the information carried by the transmitted signal is contained in the phase. Transmitted signal is defined by the Equation as:

\[
S_i(t) = \begin{cases} 
\sqrt{\frac{2g_i}{T}} \cos \left[ 2\pi ft + (2i - 1)\frac{\pi}{4} \right], & 0 < t < T \\
0, & \text{else}
\end{cases} \quad (3.3)
\]

Two orthonormal basis functions are defined by:

\[
\phi_i(t) = \sqrt{\frac{2}{T}} \cos(2\pi ft), \quad 0 < t < T, \quad \phi_2(t) = \sqrt{\frac{2}{T}} \sin(2\pi ft), \quad 0 < t < T \quad (3.4)
\]
QPSK transmitter block diagram is given in Figure 3.2. Initially, incoming sequence is converted into polar form by Polar Non-Return to Zero (PNRZ) encoder. The resultant is split into waves consisting of odd and even numbered bits by the use of a demultiplexer. The waves are then multiplied with the respective orthonormal signal functions of \( \phi_1(t) \) and \( \phi_2(t) \). The resultant waves obtained are then summed up to have the final QPSK modulated signal.

Let the QPSK modulated signal be represented by \( S_i \) where \( S_i \) is the QPSK modulated signal corresponding to input \( G_i \). Subsequently, Inverse Fast Fourier Transform (IFFT) is applied on the modulated signal to have \( F^{(i)} \), where \( 0 < i \leq K \). This signal \( F^{(i)} \) is fed into the antenna \( A_{n_i} \) and is transmitted through the channel \( Ch \). The block diagram of the receiver section is given in Figure 3.3. Consider that the system have \( m \) number of transmitter antennas and \( n_r \) number of receiver antennas. Let the FFT size be \( N_f \) and \( S_{k,r} \) be the symbol transmitted by the \( k^{th} \) antenna and \( r^{th} \) sub-carrier. Then the transmitted signal can be represented by the Equation (3.5).
\[ f_{k,r}^{(i)} = \frac{1}{N_f} \sum_{n=0}^{N_f-1} F_{k,n}^{(i)} \]  

(3.5)

Figure 3.3 Block diagram of the transmitter section

The transmitted signals are propagated through the channel before being received by the receiver antennas. Both the Rayleigh channel noise and the White Gaussian noise added with transmitted signals. Hence, the noise signal \( noi(t) \) consists of white Gaussian noise \( noi(t) \) and Rayleigh fading \( noi_f(t) \). Rayleigh fading is a statistical model for the effect of a propagation environment on transmitted signal. Rayleigh fading models assume that the magnitude of a signal that has passed through channel will vary randomly, or fade. According to a Rayleigh distribution the radial component of the sum of two uncorrelated Gaussian random variables are total noise (Bernard 1997). Hence the noise signal can be expanded as Equation (3.6).
\[ noi(t) = noi_i(t) + noi_j(t) \] (3.6)

The channel is characterized by the channel vector \( h_0 \) which is defined Equation (3.7).

\[
h_0 = \begin{bmatrix}
H_1^{(1)} & H_1^{(2)} & \cdots & H_1^{(F)} \\
H_2^{(1)} & H_2^{(2)} & \cdots & H_2^{(F)} \\
\vdots & \vdots & \ddots & \vdots \\
H_{nr}^{(1)} & H_{nr}^{(2)} & \cdots & H_{nr}^{(F)}
\end{bmatrix}
\] (3.7)

Where, \( nr \) is the number of antennas in the receiver section. Here \( H_{i}^{(j)} \) is the complex channel gain from the transmit antenna \( i \) to the receive antenna \( j \). The transmitted signals \( F^{(i)} \) are received by the antenna array which consists of \( nr \) elements.

In receiver section, the transmitted signal is received by the receiver antenna array which carried out Bayesian probability based intercarrier interference cancellation. Perfect timing synchronization is assumed. This is carried out in two cancellation stages. In the first stage, hard decision based decoding is carried out for spatial dimensions and in the second, Bayesian probability is employed.

![Figure 3.4 Block diagram of the receiver section](image-url)
The received signal at the $i^{th}$ received antenna for the $k^{th}$ OFDM symbol and the $r^{th}$ sub-carrier can be represented as:

$$x_{k,r}^{(i)} = \sum_{j=0}^{nr} h_{o}^{(i,j)} f_{k,r}^{(j)} + noi_{k,r}$$

(3.8)

$h_{o}^{(i,j)}$ is the channel parameter from the $j^{th}$ transmitting antenna to the $i^{th}$ receiving antenna which composes the MIMO channel matrix. The received signal can also be rewritten as (by removing the index values):

$$X_{k,r} = H_{r} F_{k,r} + noi_{k,r}$$

(3.9)

Where, $X_{k,r} = [x_{k,r}^{(0)}, ... , x_{k,r}^{(nr-1)}]^T$ and $(i, j)^{th}$ element of $H_{r}$ is: $h_{o}^{(i,j)m}$; The received signal is initially taken FFT and demodulated with QPSK demodulator. Let the $X_{0}, X_{1}, ..., X_{M-1}$ represent the received signal, and then FFT is given by:

$$Y_{k} = \sum_{m=0}^{M-1} X_{m} e^{-i2\pi m \frac{k}{M}}$$

(3.10)

After taking FFT, hard decision decoding is carried on spatial dimension with the use of QPSK demodulation.

FFT transformed signal is subsequently demodulated with the QPSK demodulator as shown in Figure 3.5. The FFT transformed signals are initially multiplied with the orthonormal functions ($\phi_{1}(t)$ and $\phi_{2}(t)$) and are given to the respective correlators.
Figure 3.5  Block diagram of QPSK demodulator (hard decision decoding on spatial dimension)

The correlator output signals ($y_1$ and $y_2$) are compared with the threshold set (which is zero) and hard decisions (0 or 1) are taken depending on the criteria fulfillment given in Table 3.1.

Table 3.1  Hard decision decoding table on first spatial dimension using QPSK

<table>
<thead>
<tr>
<th>Channel</th>
<th>Criteria</th>
<th>Decision taken</th>
</tr>
</thead>
<tbody>
<tr>
<td>In-phase</td>
<td>$y_1 &gt; 0$</td>
<td>1</td>
</tr>
<tr>
<td>In-phase</td>
<td>$y_1 &lt; 0$</td>
<td>0</td>
</tr>
<tr>
<td>Quadrature phase</td>
<td>$y_2 &gt; 0$</td>
<td>1</td>
</tr>
<tr>
<td>Quadrature phase</td>
<td>$y_2 &lt; 0$</td>
<td>0</td>
</tr>
</tbody>
</table>
Subsequently two decision outputs are pooled using a multiplexer to have the initial estimate of the original signal. The QPSK demodulation results in the signals represented by $Z_{k,r} = [z_{k,r}^{(0)}, \ldots, z_{k,r}^{(nr-1)}]^T$, which is taken for further processing.

Auxiliary symbol vectors are constructed from QPSK demodulated signals $z_k$ as in the Equation (3.11).

$$
\tilde{z}_k = I_z z_k
$$

Where, $I$ is the identity matrix. Receive vectors are formed from the auxiliary symbol vectors by equation given by:

$$
\check{x}_j = x - H. \tilde{z}_j, \quad 0 \leq j < M
$$

This Equation forms the parallel interference cancellation equation. In order to improve on the results and decreasing the bit error rate, Bayesian probability measure is used. This is done by incorporating Bayesian probability equation into the Equation 3.12. The modified Equation is given by:

$$
\hat{x}_j = \check{x}_j \ast \left[ \sum_{j=0}^{M-1} \frac{x}{H.\tilde{z}_j} \right] / M
$$

The obtained values are subsequently decoding to have the transmitted signal values. The threshold is set as zero, and the criteria for decision making are given in Table 3.2:
Table 3.2  Hard decision table for received signals

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Decision value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{x}_j &gt; 0$</td>
<td>1</td>
</tr>
<tr>
<td>$\tilde{x}_j \leq 0$</td>
<td>0</td>
</tr>
</tbody>
</table>

Let the final decision values be represented as $W = \{w_j\}$, where $0 \leq j < M$. The error can be calculated as the difference in original signal transmitted and the final decoded signal given by:

$$e_j = g_j - w_j, \quad 0 \leq j < M \quad \text{and} \quad E = \sum e_j \quad (3.14)$$

The total error can be computed as the summation of individual errors. Use of Bayesian probability to the parallel interference cancellation equation has resulted in successfully cancelling the interference and hence, lowering the BER and improving the reception.

3.4 RESULTS AND DISCUSSIONS

In this section, the analysis and the results of the proposed BPICI canceller is given. Comparative analysis is also made comparing the performance of the proposed technique to other prominent techniques. Analysis is carried out with the help of bit error rate curves. Section 3.4.1 describes the experimental set-up employed and in Section 3.4.2, a detailed analysis is carried out.

3.4.1 Experimental Set Up

The proposed BPICI canceller is implemented in MATLAB Version 2012 on a system having 8 GB RAM with 64 bit operating system.
having i7 Processor. For evaluation purpose, randomly generated signals in MATLAB is generated.

### 3.4.2 Performance Analysis

The bit error happens when the received bits of the data stream over a communication channel differs from the transmitted signals. This happens due to alteration of the signal which may occur due to the interference of unwanted signals, noise effects, distortions or bit synchronization errors, multipath fading, attenuation. The bit error rate or bit error ratio (BER) is the ratio of bit errors to the total transferred bits during the specified time interval. BER is performance measure used for evaluating the performance or the functionality of various methods and systems. BER plot can infer the performance of the system. $\frac{E_b}{N_o}$ is the energy per bit to noise power spectral density ratio of the received signal. $\frac{E_b}{N_o}$ is basically a normalized signal-to-noise ratio (SNR) measure of the signal.

The system for both the Rayleigh and Rician channel is considered independently and plot BER curves for both. Rician fading is a stochastic model for radio propagation anomaly caused by partial cancellation of a radio signal by itself. The signal arrives at the receiver by several different paths and at least one of the paths is changing. Rician fading occurs when one of the paths, typically a line of sight signal, is much stronger than the others. In Rician fading, the amplitude gain is characterized by a Rician distribution as per Abdi et al (2001).

Comparative analysis is made with respect to cancellation and minimum variance distortionless response. The analysis is made in two parts, first by varying the number of antennas and in the second part, length of the
user input signal is varied. In both parts the results are taken for Rayleigh and Rician channel independently.

The number of antennas is varied and BER curve is plotted in each case in this section. Results for Rayleigh and Rician channel are taken independently.

BER curves (BER vs. $\frac{E_b}{N_0}$) are plotted for varying the number of antennas for both the Rayleigh and Rician fading channels. Two cases are in consideration, one is 2 *2 (N=2), which indicates there are two antennas in the transmission and receiver section. Other case is 3 *3 (N=3), which indicates there are three antennas in the transmission and receiver section. BER curves are plotted for proposed BPIC, PIC and MVDR techniques as shown Figures.3.6, 3.7, 3.8 and 3.9.

2X2 Antenna for 100000 sample

![Figure 3.6 BER curve for N=2 and Rayleigh channel is used](image)
Figure 3.7 BER curve for N=2 and Rician channel is used

Figure 3.8 BER curve for N=3 and Rayleigh channel is used
Figure 3.9 BER curve for N=3 and Rician channel is used

The number of user signal input is fixed for $10^5$ for N=2 and 99999 for N=3. Figure 3.6 and Figure 3.8 gives the BER graph obtained for N=2 and N=3 respectively for Rayleigh channel. Figure 3.7 and Figure 3.9 gives the BER graph obtained for N=2 and N=3 respectively for Rician channel.

From the results, it is obvious that the proposed BPCI had achieved lower BER curves which shows the effectiveness of the technique. Proposed BPCI has attained lower BER when compared with PIC and MVDR. The BER curves obtained proves the validity of the technique.

The length of the user signal (represented by K) is varied, and corresponding BER curve is plotted in each case in Figures 3.10, 3.11, 3.12 and 3.13. Results for Rayleigh and Rician channel are taken independently.

The BER curves are plotted by varying the length of the user input. Both Rayleigh and Rician fading channels are considered independently. BER curves are plotted for proposed BPCI, PIC and MVDR techniques. Curves are plot for two cases in each channel for K=10^4 and K=10^5.
Figure 3.10 and 3.11 gives BER curve for Rayleigh channel for $K=10^4$ and $K=10^5$ respectively. Figure 3.12 and 3.13 gives BER curve for Rician channel for $K=10^4$ and $K=10^5$ respectively. From the results, it is seen that the proposed BPCI had achieved lower BER curves when compared with PIC and MVDR. Lower BER means that the proposed technique has performed well.

![BER curve for Rayleigh channel](image1)

Figure 3.10. BER curve for $K=10^4$ and Rayleigh channel is used

![BER curve for Rician channel](image2)

Figure 3.11. BER curve for $K=10^5$ and Rayleigh channel is used
The capacity of the MIMO systems are given by the relation

\[ C = B \log_2 \left( 1 + nT_nR_nS/R \right) \text{ bit/s} \]  \hspace{1cm} (3.14)
Where, \( n_T \) = transmitter antenna, \( n_R \) = receiver antenna

Figure 3.14 SISO vs MISO vs MIMO System

3.5 SUMMARY

Bayesian probability based intercarrier interference cancellation technique is proposed in this research work. Signals are transmitted, which propagate through the channel and is received by the receiver section. In receiver, hard decision based decoding, parallel interference cancellation and Bayesian probability are employed. The technique is implemented in MATLAB and uses BER curves as evaluation metrics. Various curves are obtained by varying the fading channel, number of user signals and number of antennas. The fading channel considered are the Rayleigh and the Rician fading channel. Experimentation is carried out for antenna size = 2 and 3. Comparative analysis is also made by comparing to other techniques such as PIC and MVDR. From the results, it is seen that the proposed technique has achieved better performance by having lower BER. Simulated Figure 3.14 Shows that MIMO 2X2 antenna capacity outperformed than SISO, MISO or SIMO and 3x3 MIMO.