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Combating ICI and Error in MANET for Indoor Communication

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***Abstract*— Mobile Ad-Hoc Network (MANET) consists of multiple mobile nodes that communicate with each other wirelessly by creating a dynamic temporary network. The primary choice for sharing of data in MANET is Orthogonal Frequency Division Multiplexing (OFDM) that promises high data rate communication and better bandwidth utilization. But the main problem with this technique is that due to the mobility of nodes in MANET Doppler frequencies are engendered that offsets the sub-carrier frequency in OFDM that degrades the error performance of the system by introducing cross talk. So Inter Carrier Interference (ICI) is introduced in the OFDM Symbols between multiple sub-carriers that disturbs their Orthogonality and degrades error performance of the system. To tone down the ICI, frequency domain (one-dimensional) channel estimation technique using Block-Type pilots is proposed in this paper. At the receiver side to nullify the ICI, frequency domain Zero-Forcing Equalization (ZFE) is used. The other problem tackled in this paper is data corruption due to noise addition during transmission. Therefore, error-correcting Turbo Codes are used which adds redundant bits in the data to trim down noise effect. At the receiver side Log- MAP decoder is used to iteratively decode the encoded bits by exchanging intrinsic information (Log-Likelihood ratio) between each elementary decoder for more accurate data detection. The simulation is done using an indoor channel model that is Saleh Valenzuela (SV) Channel with AWGN for different digital modulation schemes.**

***Index Terms*— MANET, OFDM, Inter Carrier Interference (ICI), Block-Type Pilots, Zero-Forcing Equalization (ZFE), Turbo Codes, SV Channel and Log-Map Decoder**

I. INTRODUCTION

MOBILE Ad-Hoc Network (MANET) mostly comprises power restricted mobile nodes that arrange to form a momentary network without the need of already existing infrastructure [1]. Besides other challenges in MANET like packet loss, route change due to mobility, and power adjustment of mobile nodes--high data rate transmission or reception is also a hot research topic in MANETs [2], [3]. The most promising techniques used at the physical layer of MANET to ensures high data rate communication and greater spectral efficiency is Orthogonal Frequency Division Multiplexing (OFDM). It is multi-carrier techniques which have found a number of applications. It is used in different IEEE standards like 802.16e (WiMAX), 802.11 g/n, and for Digital audio/video broadcasting, etc [4]. Implementation of OFDM at the physical layer has increased the data rate of IEEE 802.11 standard to 54 Mbps.

OFDM is better than FDM (Frequency Division Multiplexing) because in it data is modulated on multiple sub-carriers which make it more efficient in frequency selective fading channels. The sub-carriers in OFDM have sin(x)/x spectrum and they maintain the Orthogonality by coinciding the peak of one sub-carrier to the null of others as shown in Figure 1. Following property can be used to prove the Orthogonality between any two sub-carriers

$$\int_0^T \mathrm{Sin}(2\pi Jt/T)\,\mathrm{Sin}(-2\pi Kt/T)\,dt = 0,\ J \neq K \qquad (1)$$

where J and K are the frequencies of the subcarrier assigned by IFFT block. Data is modulated on these sub-carriers and therefore one OFDM Symbol can have N sub-carriers.

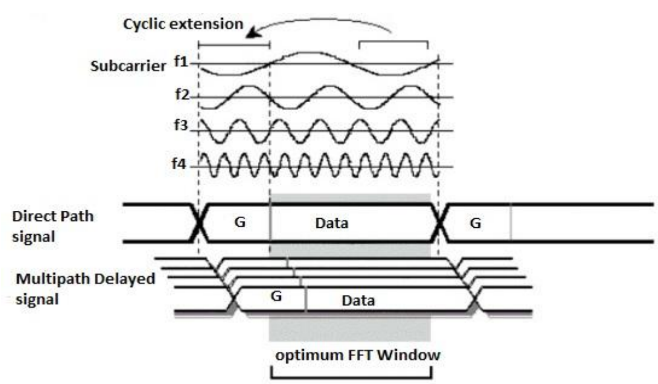

Figure 1: Cyclic Prefix Insertion in the Guard Band

Now to avoid Inter Symbol Interference (ISI), guard band is inserted between the subsequent OFDM symbols which is mostly filled by the cyclic prefix as shown in Figure 1. This guard band insertion help in accurate detection of OFDM symbols even in the presence of ISI that occurs due to multipath phenomenon and filtering effect of transmission system and channel. Other then ISI, Inter Carrier Interference (ICI) is introduced because of the mobility of transmitter and receiver in MANETs. Their mobility generates Doppler frequencies which offsets the sub-carriers frequencies in OFDM signal and disturbs their Orthogonality by misaligning the peak and null of the sub-carriers as shown in Figure 2. This results in Error-performance degradation of OFDM System.

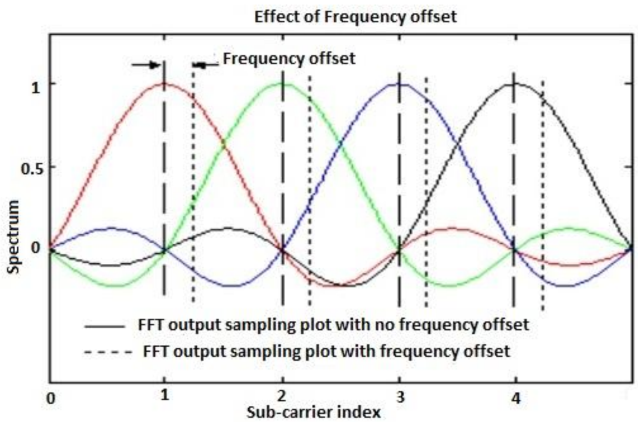

Figure 2: Frequency offset introduced by ICI

So many methods have been introduced to tone down the ICI. In [5], Won Gi Jeon *et al* worked that channel impulse response varies linearly within an OFDM symbol which becomes aberrant for high mobile environment in which the channel impulse response varies even within an OFDM symbol. In [6], Minimum Mean Square Error based channel estimation technique is proposed that is used to find the correlation of channel frequency response in both time and frequency domain. But this technique comprises complex computations that introduce processing delay. Thus its practical implementation is usually inhibited. Similarly J. Wadhwa *et al* [7] has used a self-ICI cancellation technique which utilizes extra bandwidth by modulating same data symbols on some subcarriers. Then, Maximal Ratio combining technique is used at the receiver side to retract the data symbols from subcarriers. This causes inefficient use of bandwidth which inhibits its practical use.

In this paper, ICI cancellation is achieved by applying zero-forcing equalization on OFDM signal whose frequency offset is estimated by using block-type pilots. The data symbols are detected iteratively by using Turbo Codes which shows better error-performance at low SNR. Log-Map decoder is used at the receiver side that comprises two elementary decoders that exchanges soft decisions with each other to output a hard decision about the data at the end of assigned number of iterations which helps in accurate data detection.

Rest of the paper has the following sections. Section II is the proposed OFDM System model, Section III is related to the algorithm of channel estimation and zero-forcing equalization, Section IV is about the Turbo Codes, Section V discusses the Simulation results and Section VI is the concluding remarks.

II. OFDM SYSTEM

The proposed Orthogonal Frequency Division Multiplexing System model is depicted in the Figure 3. The data is randomly generated and passed through the Turbo encoder where redundancy is added to the bits to tone down noise effect induced by the channel that enhances the error performance of the system. The code rate of 1/3 is used along with the generator matrix of constraint length K=3. After channel coding, the coded data is passed through the signal mapper block where symbols are digitally modulated using different digital modulation schemes. The data symbols are then passed through the serial to parallel converter and Inverse Fast Fourier Transform (IFFT) is applied to it. At the output of IFFT block the generated Z_k (M) OFDM Symbol contains data symbols from each sub-carrier as such

$$Z_k(M)= \{ Z_k(0), Z_k(1),\ldots\ldots,Z_k(N-1)\}^T \qquad (2)$$

Where $Z_k(M)$ is formed by modulating the input signal z(k) with the sub-carriers k=0,1,2,…..N-1. So the IFFT with size N produces at the instant k the OFDM modulated Symbol using

$$Z_k(M)= \frac{1}{N}\sum_{k=0}^{N-1} z(k) e^{-\frac{2\pi j}{N}} \qquad (3)$$

Block type pilots are also inserted in between the OFDM Symbols here for estimating the impulse response of the channel. The output signal from IFFT is then passed through parallel to serial converter and then through the Guard interval insertion block where the inserted guard band is filled with the cyclic prefix to nullify the effect of Inter Symbol Interference (ISI). Now the OFDM signal is formed and is transmitted through Saleh-Valenzuela channel which is an Indoor channel model for Mobile Ad-hoc Networks. Additive White Gaussian Noise (AWGN) is also added in the channel which corrupts the data during transmission. The received signal is first passed through the guard interval removal block where cyclic prefix is removed. It is then reshaped in serial to parallel converter block and passed to Fast Fourier Transform (FFT) block where the OFDM symbols are demodulated and block type pilots are removed for estimating the impact of channel on the signal.

Then again after reshaping the data--the OFDM symbols are equalized using the Zero Forcing equalization to cancel the negative impact of channel over it as discussed in Section III. Then after digital demodulation by signal de-mapper the data is passed through the Log-Map decoder where a specific number of iterations results in enhancing the error performance of the system. The resulting curves for different digital modulation schemes are discussed in the Section V.

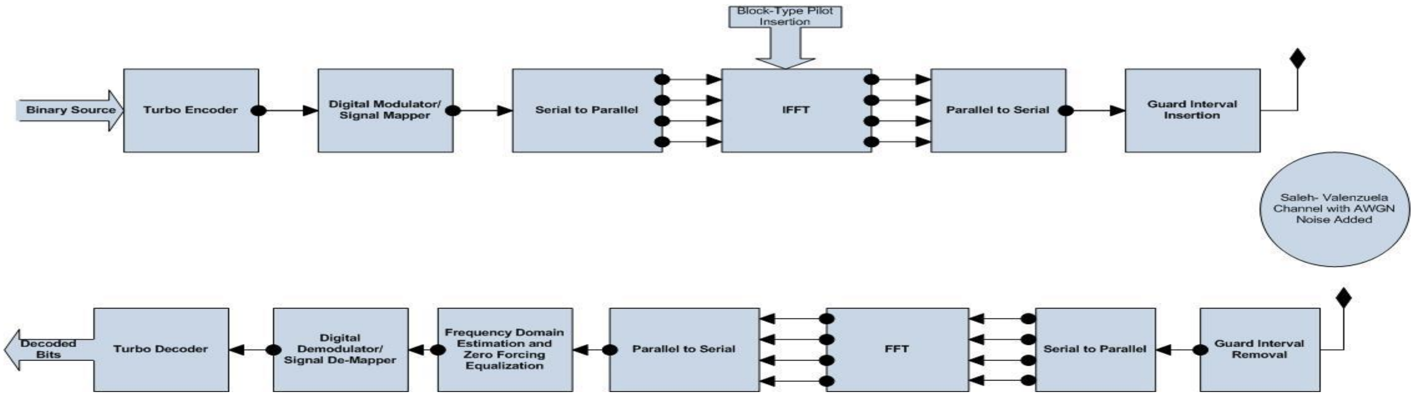

Figure 3: Proposed OFDM System Model

III. CHANNEL ESTIMATION AND ZERO-FORCING EQUALIZATION

Block-type pilot assisted channel estimation (PACE) technique is used in this paper. Block-type pilots are inserted in a single dimension after each five OFDM Symbols as shown in Figure 4. These pilot symbols are transmitted along with the OFDM Symbols—and, the receiver records the impact of the channel on it. At the receiver side, new pilot symbol of the same size and type $X_i(M)$ is generated for M=0,1,2,... N-1. Then, the following channel estimation equation is used to calculate the channel estimation matrix H_{ce}.

$$H_{ce}= Y_i(M)/ X_i(M) \quad (4)$$

Where $Y_i(M)$ is the received Pilot Symbol, and "i" is the index to the number of pilot symbol.
Once H_{ce} is calculated, then zero-forcing equalization is used to nullify the impact of channel on the upcoming OFDM Symbol by using the following equation

$$R(M)= T(M)/ H_{ce} \quad (5)$$

T represents the received OFDM Symbol, and R is the equalized OFDM Symbol. This same procedure is repeated for every upcoming OFDM Symbol until the next pilot symbol arrives.

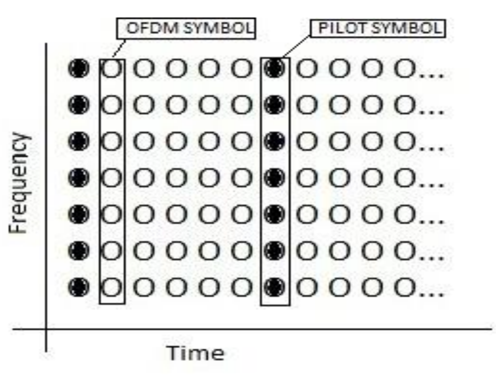

Figure 4: Block-type pilot symbols within OFDM symbols

IV. TURBO CODES

Turbo codes are FEC codes that show high performance that is close to the Shannon limit when compared with its contemporaries [8].It has reduced the energy requirement for transmitting data in OFDM Systems. In [9], Claude Berrou *et al.* introduced it in 1903—and, by then it has been worked to increase the complexity of the decoding algorithm to achieve performance near shannon's bound [10]. High error performance is achieved by the use of interleaver in the encoder and iteratively decoding the data [11]-[13]. Turbo codes are available in both Parallel Concatenated Convolutional Codes (PCCC) structure and Serially Concatenated Convolutional Codes (SCCC) structure. SCCC contains only one recursive systematic convolutional code and performs better at high SNRs. But, PCCC have both recursive systematic convolutional codes and performs better at lower SNRs [14]. This paper uses PCCC version of Turbo Codes. Data is encoded using PCCC and Log-Map decoding algorithm is used to iteratively decode it at the receiver side. The increase in the number of iteration results in more accurate detection of data. This behaviour is similar to turbo engines used in cars; therefore, it is named as Turbo Codes.

A. *Encoding*

The encoder used in this paper is formed by the parallel concatenation of two recursive systematic convolutional encoders with a S-random interleaver in-between as shown in Figure 5. The S-random interleaver also known as spread interleaver was introduced by Divsalar and Pollara [15]. It generates N integers randomly with a minimum interleaving distance called S-constraint. It compares each of the randomly selected integer with S_1 previously selected one. If the absolute value of the difference between any of the S_1 previously selected integer and the current randomly selected integer is less than S_2 then it is discarded [16]. This process is repeated until all integers are selected. This is given by the following equation (6).

$$|C_1 - C_2| \geq S_2 \quad (6)$$

where S1 and S2 are chosen such that:

$$S1, S2 < \sqrt{\frac{N}{2}} \qquad (7)$$

The interleaver in the encoder has three purposes, one is to jumble up the data bits for the EC2 and make its output different from EC1. Second is to make possible divide-n-conquer strategy at the decoder. So, half of the bits are decoded with one elementary decoder and the other half of the bit is decoded with other elementary decoder—and, both work collaboratively to come up with more accurate detection of data. Third is to distribute the error in different block of data to make burst error correction easy.

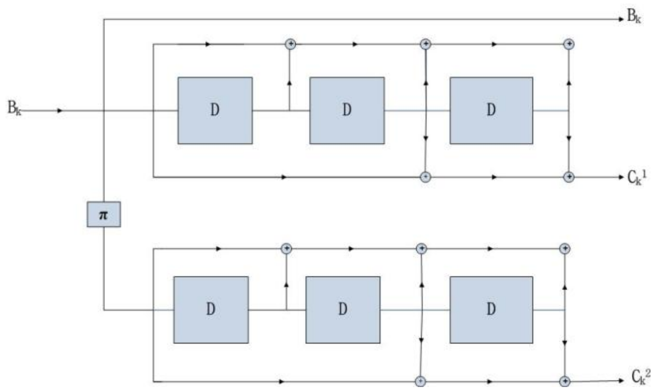

Figure 5: Turbo Encoder with code rate of 1/3

B_k = { B_0, B_1, ..., B_N} is the input bit stream that is provided to turbo encoder. At the output of EC1 and EC2, we get C_k^1 = {C_0^1, C_1^1, ..., C_N^1} and C_k^2 = {C_0^2, C_1^2, ..., C_N^2} bit stream respectively. EC1 and EC2 use the generator matrix [1 1 1 1; 1 0 1 1] having constraint length 3. The table for the eight possible states of recursive systematic convolutional encoder is given in Table 1:

Table 1: Possible states for RSC encoder with K=3

State No.	D1	D2	D3
0	0	0	0
1	0	0	1
2	0	1	0
3	0	1	1
4	1	0	0
5	1	0	1
6	1	1	0
7	1	1	1

At the output of turbo encoder we get the following bit stream X= {B_0 C_0^1 C_0^2 B_1 C_1^1 C_1^2 B_2 C_2^1 C_2^2.....}, the subscript indicates the time index and the superscript indicates the bit from the corresponding encoder. Figure 6 shows the state diagram for each convolutional encoder concatenated in parallel.

B. Turbo decoding

Log-Map decoder is used to decode the received data bits. It contains two elementary decoders that are connected by

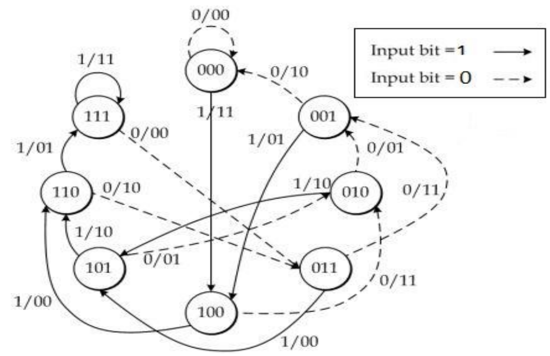

Figure 6: The state diagram for PCCC

means of interleaver/ de-interleaver as shown in Figure 7. Each one calculates the log-likelihood ratio or a-posteriori value in the log-domain by using the Log-Map algorithm [16]. The a-posteriori value is calculated by using the following equation (8).

$$LLR = \max_{(k,k'),J=1}[\ln \gamma_{t+1}(k,k') + \ln \beta_{t+1}(k) + \ln \alpha_t(k,k')] \\ -\max_{(k,k'),J=-1}[\ln \gamma_{t+1}(k,k') + \ln \beta_{t+1}(k) + \ln \alpha_t(k,k')] \quad (8)$$

where alpha (α) is the forward metric, Beta (β) is the backward metric, and gamma (γ) is the branch metric of the trellis diagram. k is the initial state and k' is the final state in the trellis diagram as discussed in [15].The interleaved/de-interleaved version of this a-posteriori value is called the a-priori value, which is fed to the elementary decoders along with the systematic and parity bit. Each decoder uses these three values to calculate the extrinsic information or Log-likelihood ratio. For the first iteration of Turbo decoder, a-priori value is chosen as 0, as DEC1 does not know that what DEC2 has calculated. Then, there is an uninterrupted exchange of this extrinsic information for the selected number of iteration between the two elementary decoders. At the end, the DEC2 outputs a hard decision of bits. In Log-Map decoder, the Log-likelihood ratio is calculated by dividing the trellis diagram into two possible courses, the best course with the probability of one and the best course with the probability of zero, then, Log-likelihood ratio is calculated for these two paths separately--there difference gives the extrinsic information.

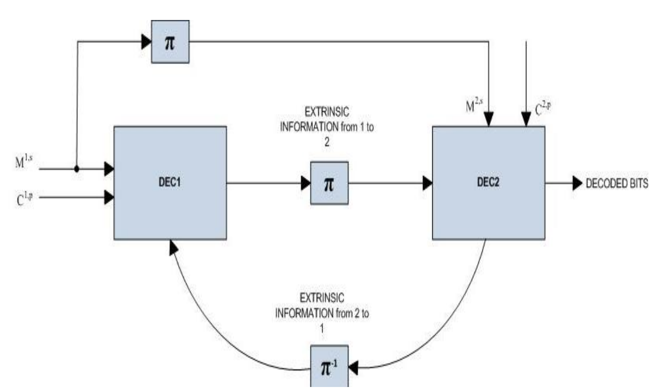

Figure 7: Log-Map Decoder comprised of two elementary Decoders

V. PERFORMANCE AND SIMULATION RESULTS

The simulation of the Coded OFDM System with block-type pilots assisted channel estimation and Zero-Forcing Equalization (ZFE) in Saleh-Valenzuela channel is done in Matlab 7.0 ® for different digital modulation schemes. The results are discussed below for both the un-coded OFDM System and Coded OFDM System. The OFDM Signal is transmitted by the circular antenna lying at the origin of Cartesian coordinate system with vertical polarization and operating at 1 GHz. The Saleh-Valenzuela (SV) Channel is used with 6 clusters and 10 rays per cluster. The clusters slope rate is chosen to be 1/100e-9 and the rays within the cluster have the slope rate of 1/5e-9. The time constant for cluster and rays is 300e-9 and 90e-9 respectively. The delay of first ray is chosen to be 1.0007e-7 and the K-factor is chosen to be 4 dB for indoor communication with line of sight availability between transmitter and receiver. The receiving antenna is lying at x=-0.2269, y= -0.0737, and z=0 in Cartesian coordinate system and has the same polarization and type as of transmitting antenna. AWGN is also added to the channel to corrupt the data in a high mobile environment.

1) Un-coded OFDM System with PACE and ZFE:

To simulate the BER vs. SNR curves for the un-coded OFDM System, OFDM symbol with 2048 subcarriers is taken and 25% cyclic prefix is added to it to mitigate the ISI. Block-type pilot symbol is inserted after every five OFDM Symbols to efficiently nullify ICI at the receiver side.

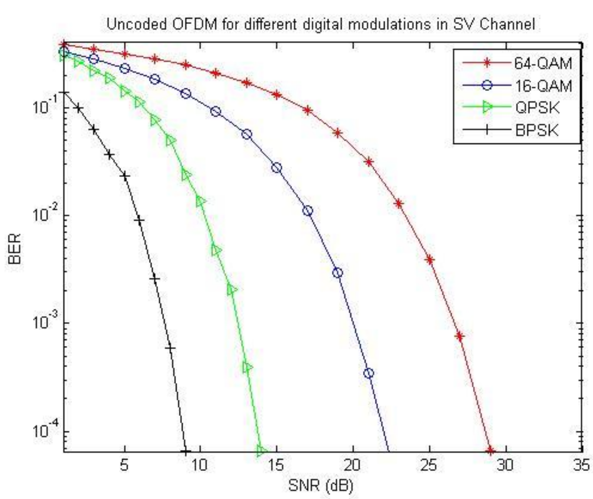

Figure 8: Curves for Un-Coded OFDM in SV channel with AWGN

The simulated curves for the un-coded OFDM with PACE and ZFE is shown in Figure 8. It is observed that for high modulation schemes, the performance of the system degrades. This is because the data symbols in the constellation diagram come more close to each other—and, the decision boundaries are difficult to separate which degrades the error performance of the system. In [17], Said Elnoubi *et al* proposed Comb-type pilots for estimating the impact of channel on OFDM signal. It uses linear interpolation at the receiver side for estimating data on the places where pilots are missing that inserts error in the estimation of channel impulse response. In this paper, Block type pilot symbols accurately estimate the impact of channel on all sub-carriers in an OFDM symbol that improves the performance of OFDM System. Thus, when the curve for QPSK in Figure 9 is compared with the QPSK curve in [17], then it is seen that at the BER of 10^{-3}, block-type pilot assisted channel estimation and zero-forcing equalization results in a coding gain of 12.5 dB.

2) Coded-OFDM System with PACE and ZFE:

For this section, the same OFDM System is taken with IFFT/FFT size of 2048 and Guard Interval length of 25%. The effect of the Turbo-Codes on the performance of OFDM System with block-type pilots assisted channel estimation and Zero-forcing equalization is noted for the same digital modulation schemes as used for un-coded OFDM system. The importance of iterations in Log-Map decoder in achieving high coding gain is also discussed in this section. The same SV channel is used here as well.

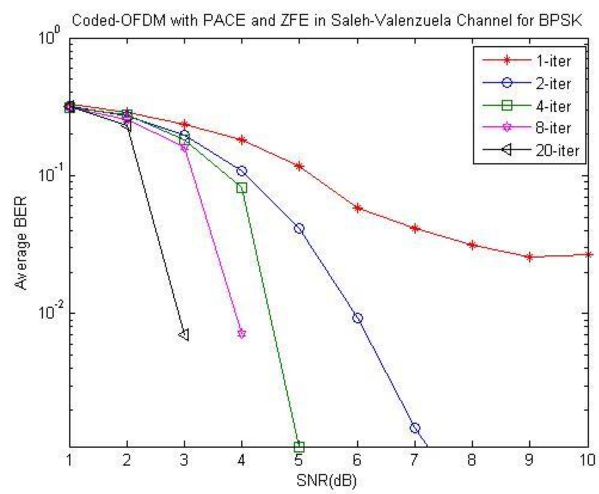

Figure 9: Curves for different iterations of Log-Map decoder for BPSK in SV channel with AWGN

By comparing Figure 9 with Figure 8, we can see that the increase in the number of iterations provides more coding gain. This is because of sharing of extrinsic information also called Log-likelihood ratio between two elementary decoder that goes bigger by increasing the number of iterations, thus, resulting in more accurate detection of data. For the BER of $10^{-2.4}$, coding gain of 3 dB is obtained from 8 iterations and 3.9 dB is obtained from 20 iterations.

The SNR vs. BER curves for QPSK, 16-QAM, and 64-QAM is shown in Figure 10, 11, and 12 respectively. The parameters of the Coded-OFDM System are kept same for them. In [18], V. Chaturvedi *et al* has showed the performance of Random Interleaver in Turbo Coded OFDM System. When these figures (10, 11, and 12) are compared with those figures in that paper--at the BER of $10^{-2.4}$, coding gain of 3 dB is achieved for BPSK and 2.6 dB for QPSK. This proves that S-Random interleaver used in this paper performs better than Random interleaver.

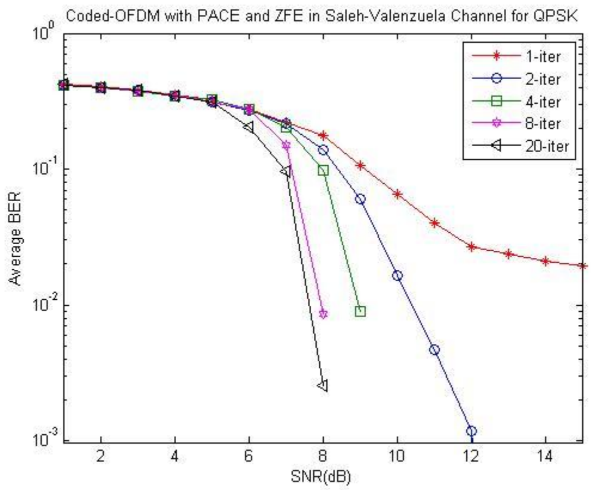

Figure 10: Curves for different iterations of Log-Map Decoder for QPSK in SV channel with AWGN

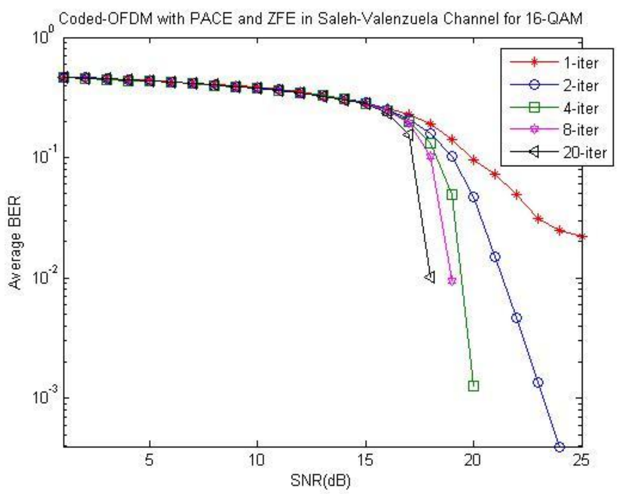

Figure 11: Curves for different iterations of Log-Map Decoder for 16-QAM in SV channel with AWGN

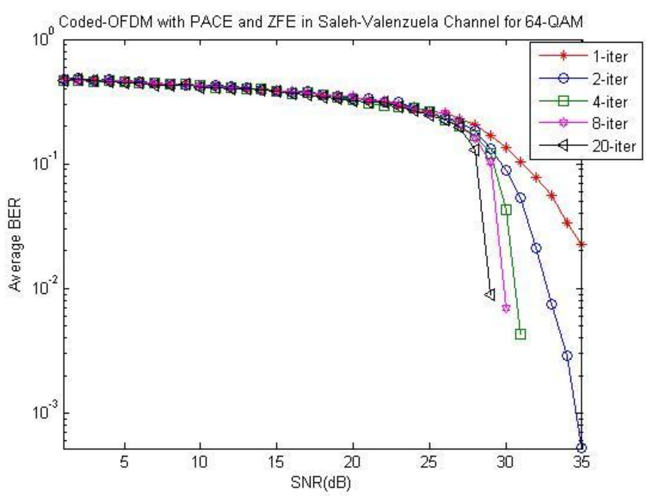

Figure 12: Curves for different iterations of Log-Map Decoder for 64-QAM in SV channel with AWGN

When Figure 10 – Figure 13 are compared with Figure 9, it is seen that for higher digital modulation schemes, the increase in coding gain reduces by increasing the number of iterations of Turbo decoder. It is because the data symbols come more close to each other and thus the chances of error increases. This degrades the error-performance of Log-Map decoder in OFDM System. Different factors like through put, bandwidth, data rate, and complexity, etc, is considered for choosing specific modulation scheme.

VI. CONCLUSION AND FUTURE WORK

The curves for Average BER vs. SNR for different digital modulation schemes are plotted for different iterations of Log-Map decoder. It is observed that block-type pilots assisted channel estimation and Zero-forcing equalization has shown improvement in performance of OFDM System than comb-type pilot assisted channel estimation used in [17]. Moreover, turbo codes have also helped in achieving more coding gain in OFDM System. But the error performance reduces for higher modulation schemes which are because of the close placement of data symbols that increase the chances of error. This Zero-Forcing Equalization can be applied to comb-type and lattice-type pilot aided estimation technique to evaluate its performance for channel estimation and equalization.

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