Error Rate Performance of Interleaved Coded OFDM For Undersea Acoustic Links

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Abstract

Studies on undersea acoustic communication links, set up through highly complex and inhomogeneous underwater channel using various orders of QAM and PSK based OFDM techniques, have been reported in open literature. However, their bit error rate performances still need to be improved. Coding, when combined with OFDM, helps to detect and correct errors without having the overhead of too many retransmissions, as the bandwidth is a scarce resource in undersea scenario. The technique of interleaving, which is frequently employed in digital communication and storage systems to enhance the performance of the coding schemes, can be used to improve the error rate performance of the coded OFDM. The error rate performances of interleaved convolutional and BCH coded OFDMs for undersea acoustic links for binary phase shift keying and its differential variant have been studied in this paper. It is found that at high SNR, the process of interleaving and coding offers significant improvement in the error rate performance. It is also worth mentioning the fact that interleaving improves the performance of both convolutional and BCH coded OFDM systems.

Keywords: Coding, Constraint Length, Interleaving, Sound Speed Profile, Undersea Links.

1. INTRODUCTION

The oceans possess significant explored as well as unexplored marine living and non-living resources which necessitates the need and requirements for the exploration and *in-situ* online almost real time, monitoring of the ocean in a general perspective. As radio frequency waves are not suitable for undersea communication, due to high attenuation in water, acoustic waves are used as the mode of communication in undersea wireless networks, though it suffers from innumerable constraints and limitations [1-3] such as low bandwidth, high and variable latency, power constraints, high failure rate, unpredictable propagation characteristics, multipath effects, etc.. The high failure rate constraint of undersea networks demand improvements to the existing communication techniques. During the last three decades, the realm of undersea communication scenario has witnessed remarkable progress and there was a migration from systems with low bit rate to high bit rate and high power to low power consumption, which facilitated the widespread development and deployment of undersea acoustic networks. Current research in this area focuses on judicially formulating an integrated solution for meeting the emerging demands for applications of undersea networks [4, 5] in environmental data collection, pollution monitoring, offshore surveillance, coastal surveillance, etc..

Orthogonal Frequency Division Multiplexing (OFDM) [6, 7] has gained remarkable attention because, the combination of high data capacity, high spectral efficiency, and its resilience to interference due to multipath effects indicate that it is an ideal choice for underwater acoustic communication scenario. The bit error rate performance of normal OFDM for undersea acoustic links still needs to be improved [7, 8]. Coding [9], which helps to detect and correct errors without having the overhead of much of retransmissions, can be combined with OFDM. Coding helps to improve the transmission efficiency, security, quality and reliability. The technique of interleaving [10], which is frequently employed in digital communication and storage systems to enhance the performance of the coding schemes, can be used to improve the error rate performance of the coded OFDM. A comparison of Coded OFDM (COFDM) with OFDM has been made for noisy environments in [11] and it has been shown that COFDM outperforms OFDM with respect to BER performance. However, the performance of COFDM for undersea acoustic links needs to be simulated. In this paper, coding and interleaving schemes have been combined judiciously so as to improve the error rate performance of the undersea acoustic communication system. The paper is organized as follows. Section 2 gives the propagation characteristics of undersea acoustic medium, while Section 3 discusses the modulation schemes and subcarrier generation for orthogonal frequency division multiplexing as well as signal estimation at the receiver. Section 4 discuss the channel coding schemes like convolutional and BCH coding as well as interleaving schemes used in communication for improving the error rate performance. Section 5 discusses the simulation of coded OFDM systems with and without interleaving. Section 6 presents the results of all the proposed OFDM schemes while Section 7 gives an overview of the highlights of the simulation studies.

2. UNDERSEA ACOUSTIC CHANNEL

The sound speed profile (SSP) in sea water determines the behavior of sound propagation in the sea and it varies with location, depth, temperature, etc.. The sound speed profile represents a plot of the speed of sound with depth and it may be constructed from a number of field measurement data and then subjecting it to a fitting algorithm to generate a smoother graph. Given the conductivity, temperature, depth (CTD) data, the Sound Speed can be computed using the equation,

$$C = 1492.9 + 3(T-10) - 6\times10^{-3}(T-10)^2 - 4\times10^{-2}(T-18)^2 + 1.2(S-35) - 10^{-2}(T-18)(S-35) + \frac{z}{61} \quad (1)$$

where C is the sound velocity in m/s, T is the temperature in degree Celsius, S is salinity in parts per thousand and z is the depth in meters.

Sound Speed Profile for a real ocean region with the collected CTD data and computed using (1) is shown in Figure 1. It can be seen that the sound speed varies non-linearly with the depth. This nonlinearity is due to the variation of temperature, salinity and pressure with depth. At lower depths, the temperature determines the sound speed, but as the water depth increases, the pressure tends to be a decisive factor in influencing the speed of sound propagation in water. If sound speed profile for the desired location can be obtained, it gives more realistic results, when used for simulation, rather than using an assumed sound speed profile. Multipath effects in water are due to reflections of sound from the sea surface and sea bottom as well as due to sound refraction in the water [12]. As a result, the receiver gets a bewildering mix of signals from the transmitter in direct path as well as multipaths. Assuming α_i to be the amplitude associated with the i^{th} path, multipath can be modeled as

$$\boldsymbol{h} = \sum_{i=1}^{N} \alpha_i \, \delta(\tau - \tau_i) \quad (2)$$

where N is the number of multipaths and τ_i is the i^{th} path delay.

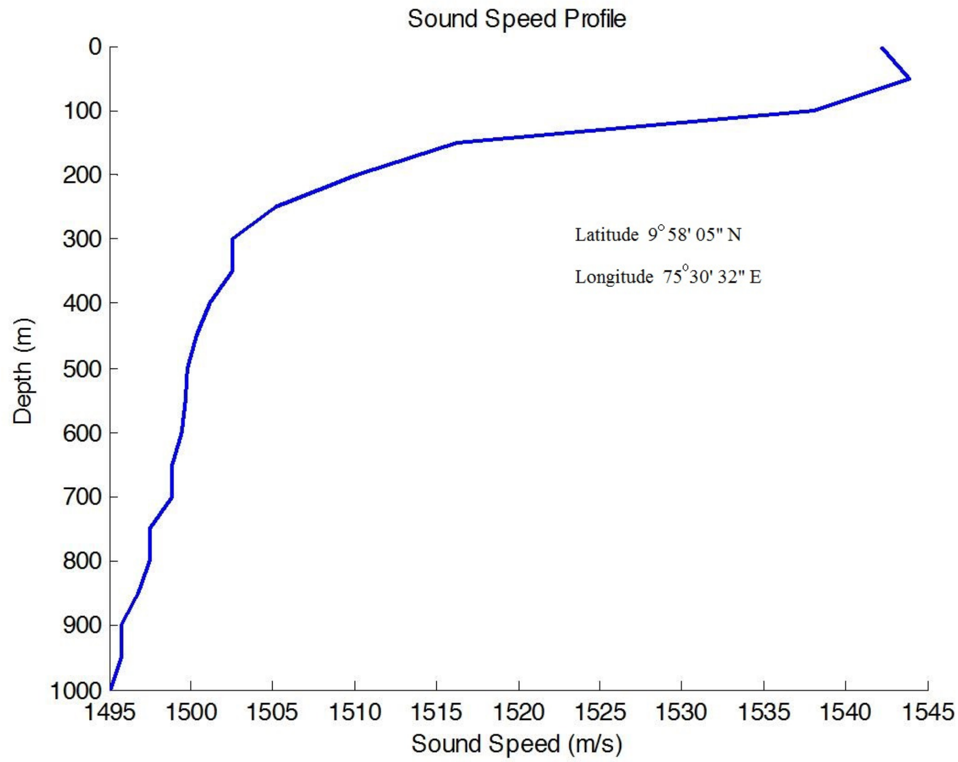

FIGURE 1: A typical sound speed profile from real ocean.

Sea trials being very expensive, undersea acoustic communication scenario is normally simulated with any of the available toolboxes. Bellhop [13, 14] is a highly efficient, versatile and widely used ray tracing toolbox for predicting the acoustic pressure fields in ocean environments. Bellhop can produce a variety of useful outputs including the transmission loss, eigen rays, channel impulse response, etc. for the environment specified by the user. To utilize the ray tracing capabilities of the Bellhop effectively, a precise description of the physical characteristics of the environment is important. This includes the depth of the region, sound speed profile in that region, information concerning the bottom contour and roughness, information about the surface, etc.. The environmental data can be extracted from the real time measurements or it can be obtained from the data banks for the particular ocean environments. Generally, real time measurements are preferred so that the model will compute more realistic results. The environmental data should include the frequency of operation, depth-speed pairs, number of sources, receivers and their depths, etc.. The channel impulse response has been generated in this paper using the Bellhop based on a modeled undersea scenario and the multipath propagation modeling is carried out by tracing a large number of rays through the inhomogeneous undersea acoustic channel that is characterized by the given sound speed profile and the rays are traced by numerically solving the differential ray equations given in [15]. The resulting rays no longer travel on straight lines due to the variation of sound speed with depth. The Bellhop model considers cylindrical spreading loss, which occurs when the medium has plane parallel upper and lower bounds and is governed by:

$$\textit{Transmission Loss} = 10 \log r \quad (3)$$

where r is the range from the transmitter. The Thorpe attenuation model, which describes the conversion of acoustic energy into heat, gives the extent of the absorption loss, when the sound propagates through the medium and is given by

$$\alpha(f) = 0.11\frac{f^2}{1+f^2} + 44\frac{f^2}{4100+f^2} + 0.0003f^2 + 0.0033 \quad (4)$$

where α is the attenuation in dB/km and f is the frequency in kHz. Thus, for a given distance traversed, the sound intensity gets diminished due to absorption as well as spreading. In this paper, the channel impulse response has been generated using the Bellhop model, assuming a source depth of 50m, receiver depth of 100m, receiver range of 1km and ocean depth of 1km.

3. ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

OFDM, which is widely employed nowadays, is a multicarrier modulation technique which makes effective use of the available bandwidth. It divides the available frequency spectrum into a number of sub bands. The data stream is also divided into several parallel data streams of lower rates and the individual subcarriers are modulated by individual low rate data streams and the resultant signals are combined and transmitted [6].

3.1 Subcarrier Generation

The modulation of the binary input is carried out by any of the schemes like QAM, FSK, PSK and their variants. Differential Phase Shift Keying (DPSK), which is a differentially encoded BPSK signal, is often used instead of BPSK, in practice, since DPSK receiver does not require a carrier synchronization circuit. In DPSK, the information is represented with relative phase, rather than the actual phase of the carrier. The subcarriers of OFDM are modulated by the symbols generated from binary input and these subcarriers are made orthogonal so that the inter carrier interference (ICI) effect is reduced. If $X_0, X_1, \ldots X_{M-1}$ are the M symbols and $\phi_0[n]$, $\phi_1[n]$, ... $\phi_{M-1}[n]$ are the M subcarriers, then the resulting signal is:

$$x[n] = X_0\phi_0[n] + X_1\phi_1[n] + \ldots + X_{M-1}\phi_{M-1}[n] \quad (5)$$

The most popular set of orthogonal subcarriers can be generated by computing the IDFT. Thus,

$$x[n] = \frac{1}{\sqrt{M}}\sum_{i=0}^{M-1} X_i e^{j\frac{2\pi in}{M}} = IDFT\{X\} \quad (6)$$

and can be easily implemented using IFFT efficiently. These orthogonal subcarriers being overlapping, helps OFDM to achieve comparatively higher spectral efficiency.

3.2 Signal Estimation

The use of zero padding or cyclic prefix guard band eliminates the inter symbol interference, if the length of guard band is greater than the length of channel impulse response. The cyclic prefix converts the channel effect into circular convolution, which corresponds to multiplication in the frequency domain. Equalizers, which are widely used in practical communication systems, help to undo the channel effects such as the multipath, inter symbol interference, etc.. OFDM enables simpler equalization at the receiver, which can be accomplished by a simple single tap frequency domain equalizer. This is equivalent to assuming that any fading is flat across the bandwidth of each subcarrier and the estimated signal at the receiver is given by:

$$\hat{X}(f) = \frac{Y(f)}{H(f)} \quad (7)$$

where $Y(f)$ and $H(f)$ are the frequency domain counterparts of the received signal $y(n)$ and the channel impulse response $h(n)$ respectively.

4. CHANNEL CODING AND INTERLEAVING

Channel coding addresses the process of mapping message vectors into code vectors using certain well defined mapping procedures in such a way that the errors in the overall system can be corrected at the receiving end, leading to improved error rate performance.

Convolutional coder [16] encodes the bit streams continuously using a sequential logic in accordance with the coupled memory of the coder. For the purpose of generating the coded symbols, the input stream is fed into a *k*-stage shift register and the shift register contents are combined modulo-2 in such a way that the coder generates the resultant code vector in accordance with certain generator polynomial criteria. The nonsystematic convolutional codes have been used for error correction using the Viterbi decoding algorithm. The Viterbi maximum likelihood algorithm is found to be a very effective decoding procedure for codes with small constraint lengths. BCH code [16], which is a variant of the block code as well as a subclass of cyclic codes, has powerful built in properties for multiple error corrections and are supplemented with computationally efficient codec algorithms. Decoding of BCH codes involves computing the syndrome from the received code words, finding the error locations from the syndrome and finally correcting the errors.

The errors occurring in a real communication scenario are often burst errors, which starts and ends with an error, the bits in between may or may not be erroneous. This results in unacceptable error rate performances in certain observation intervals [17]. This problem can be resolved to some extent by changing the order of the sequence of transmitted symbols by the process of interleaving and recovering the original order of sequence of the symbols at the receiver by a deinterleaver. The error bursts thus occurring due to channel effects get fairly distributed over time, resulting in an acceptable error rate performance.

5. SIMULATION STUDIES

The system model for interleaved coded OFDM is similar to the one for the normal OFDM, except the encoding and interleaving at the transmitter side as well as deinterleaving and decoding at the receiver side. The Block Diagram of the Interleaved Coded OFDM is as shown in Figure 2. The data stream comprising of 64 bits per OFDM symbol has been encoded using convolutional and BCH coding for the purpose of validating their performances. Convolutional coding has been performed by an encoder with a constraint length 7 and code rate 1/2, where as a BCH (7,4) coding has been performed on 64 bits resulting in 112 bits. Thus 128 and 112 sub carriers per OFDM symbol are required for convolutional coded and BCH coded OFDMs respectively. This data has further been subjected to interleaving, followed by the BPSK and DPSK based OFDM modulations. If the channel is one which produces burst errors, an effective technique to reduce these errors is to shuffle the coded data through the method of interleaving in such a way that the error bursts get fairly and uniformly distributed in time. By doing so, the bursty channel effect is being manipulated into a channel characterized by independent errors. The data with 128 bits and 112 bits are written row-by-row into a 16 x 8 matrix for convolutional coded OFDM and 14 x 8 matrix for BCH coded OFDM respectively and read out column-by-column by the interleaver. The reverse process is performed by the deinterleaver at the receiver. The transmitted signal contaminated with the background noise is then convolved using the channel impulse response generated by the Bellhop model which can be modeled as:

$$\boldsymbol{y}(\boldsymbol{n}) = [\boldsymbol{x}(\boldsymbol{n}) + \boldsymbol{a}(\boldsymbol{n})] \otimes \boldsymbol{h}(\boldsymbol{n}) \tag{8}$$

where *x(n)* is the transmitted signal, *a(n)* is the ambient noise, *h(n)* is the channel impulse response and *y(n)* is the received signal.

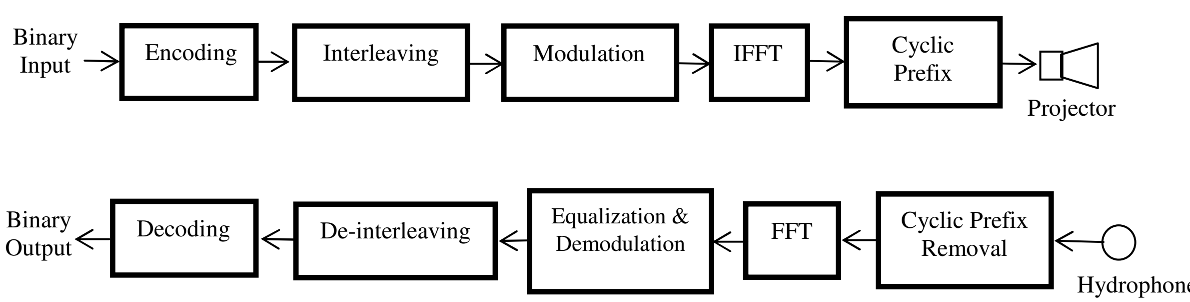

FIGURE 2: System Model of Interleaved Coded OFDM.

At the receiver, the OFDM demodulated signal is subjected to deinterleaving followed by decoding for regenerating the original data stream. The bit error rate performances, under various Signal to Noise Ratio conditions, have been simulated for BPSK and DPSK based convolutional coded OFDM with and without interleaving as well as BCH coded OFDM with and without interleaving. Also, the effect of interleaving has been investigated by quantitatively comparing the performances of both the coded OFDM schemes, with and without interleaving.

6. RESULTS AND DISCUSSIONS

The bit error rate performances have been computed by pumping out 10^8 bits under various SNR conditions using the BPSK and DPSK mapping schemes, convolutional as well as BCH coding schemes with and without interleaving. The center frequency of the OFDM band is taken to be 10 kHz and it is assumed that the receiver has complete channel information. A bandwidth of 10 kHz can be chosen for medium range applications for underwater acoustic channels. In the simulation, perfect frequency and phase synchronization are assumed. The parameters used for simulating the convolutional coded as well as BCH coded OFDM systems are furnished in Table 1. The number of subcarriers needed for the present simulation studies are 128 and 112, per OFDM symbol for convolutional coded and BCH coded OFDMs respectively.

Parameter	Convolutional Coded OFDM	BCH Coded OFDM
No. of transmitted bits	10^8	10^8
Mapping Scheme	BPSK, DPSK	BPSK, DPSK
Carrier frequency	10kHz	10kHz
Signal frequency band: BW	10kHz	10kHz
Number of subcarriers: N	128	112
Subcarrier bandwidth: Δf = BW/N	78.125Hz	89.285Hz
Valid symbol duration	12.8ms	11.2ms

TABLE 1: Simulation Parameters.

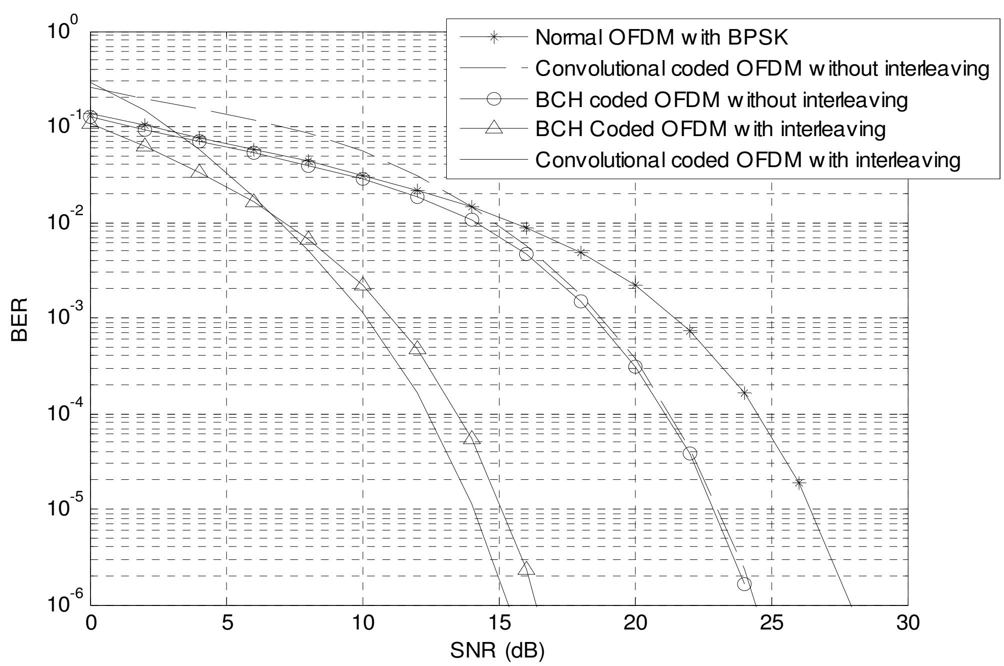

FIGURE 3: Comparison of BER performances of normal OFDM with Convolutional Coded and BCH coded OFDMs, with and without interleaving for an undersea communication channel using BPSK modulation.

Comparing the performances of BPSK and QPSK, even though QPSK offers higher spectral efficiency, it has been observed that BPSK based OFDM offers lower bit error rates. This is because, for higher order PSK, the number of points in the constellation plot increases, thus reducing the spacings between the points. Hence, BPSK based OFDM has been used for simulation. Figure 3 shows the BER performances of BPSK based normal OFDM, convolutional coded OFDM as well as BCH coded OFDM with and without interleaving. It can be observed that both the coded OFDM schemes with interleaving perform better than normal OFDM. The error rate of convolutional coded OFDM is high compared to BCH coded OFDM upto a crossover SNR value; beyond which the error rate of the convolutional coded OFDM with interleaving decreases. BCH coded OFDM with interleaving offers lower BER compared to normal OFDM at all SNR values. It has also been observed that coded schemes with interleaving perform much better than their counterparts without interleaving. As a result of interleaving and deinterleaving, error bursts get spread out in time and hence, the process of interleaving improves the error rate performance of the coded OFDM system. Thus, it can be concluded that both the convolutional and BCH coded OFDM systems with interleaving offers commendable improvement in performances.

The performances of coded OFDM techniques with and without interleaving have also been simulated for DPSK based OFDM systems and the results of this simulation are depicted in Figure 4. From figures 3 and 4, it can be observed that DPSK based system performs less efficiently compared to BPSK based OFDM system, because in DPSK errors tend to propagate. DPSK based OFDM systems are also found to perform well when the data is subjected to coding and interleaving. Thus, in addition to improving transmission security, coding combined with interleaving offers significant improvement in bit error rate performances.

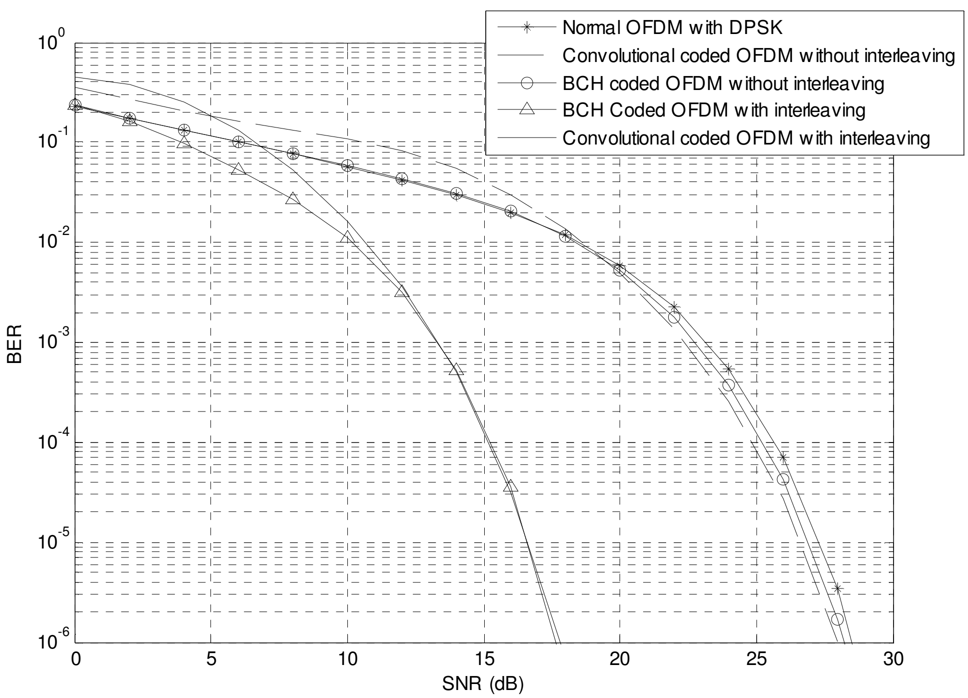

FIGURE 4: Comparison of BER performances of normal OFDM with Convolutional Coded and BCH Coded OFDMs, with and without interleaving for an undersea communication channel using DPSK modulation.

The BER values of all the OFDM techniques for various SNR levels for BPSK and DPSK based OFDM systems are tabulated in Tables 2 and 3 respectively. In the case of BPSK based systems, for SNR above 8dB, coded OFDM with interleaving shows tremendous improvement in performance compared to their counterparts without interleaving, whereas in DPSK based OFDM systems, for SNR above 12dB, coded OFDM systems with interleaving performs much better when compared to their counterparts without interleaving. Thus, coding when suitably combined with interleaving, improves the performance of the system significantly. Moreover, as can be seen from the Tables 2 and 3, the bit error rate performance of BPSK based interleaved convolutional coded OFDM is superior when compared to the DPSK based system assuming perfect frequency and phase synchronization.

SNR (dB)	Normal OFDM	BCH coded OFDM	Convolutional coded OFDM	BCH coded OFDM	Convolutional coded OFDM
		(without interleaving)		(interleaved)	
0	0.1374	0.1243	0.2530	0.1081	0.2911
2	0.1032	0.0936	0.1945	0.0627	0.1507
4	0.0773	0.0710	0.1520	0.0333	0.0571
6	0.0579	0.0534	0.1168	0.0161	0.0181
8	0.0430	0.0394	0.0843	0.0067	0.0051
10	0.0312	0.0280	0.0543	0.0022	0.0011
12	0.0219	0.0184	0.0302	0.47592×10^{-3}	0.16563×10^{-3}
14	0.0145	0.0104	0.0143	0.5509×10^{-4}	0.1143×10^{-4}
16	0.0089	0.0046	0.0056	0.2340×10^{-5}	0.33×10^{-6}

TABLE 2: Bit Error rates for BPSK based OFDM systems under various SNR condition.

SNR (dB)	Normal OFDM	BCH coded OFDM	Convolutional coded OFDM	BCH coded OFDM	Convolutional coded OFDM
		(without interleaving)		(interleaved)	
0	0.2304	0.2345	0.3569	0.2393	0.4509
2	0.1751	0.1762	0.2727	0.1606	0.3801
4	0.1314	0.1323	0.2070	0.0967	0.2558
6	0.0996	0.1006	0.1638	0.0539	0.1309
8	0.0758	0.0768	0.1331	0.0270	0.0522
10	0.0571	0.0579	0.1077	0.0111	0.0162
12	0.0421	0.0430	0.0820	0.0032	0.0037
14	0.0298	0.0307	0.0545	0.5237×10^{-3}	0.49867×10^{-3}
16	0.0198	0.0203	0.0302	0.3575×10^{-4}	0.3106×10^{-4}

TABLE 3: Bit Error rates for DPSK based OFDM systems under various SNR condition.

7. CONCLUSIONS

The bit error rate performances of normal as well as coded OFDM with and without interleaving schemes have been simulated for various signal-to-noise ratio levels. For BPSK based OFDM, the BCH coder with interleaving gives better performance compared to convolutional coder with interleaving for very low SNR values, whereas for SNR levels higher than 8dB, convolutional coder with interleaving gives improved error rate performance. However, for DPSK based OFDM, the error rate performance of BCH coded system with interleaving is found to be better for SNR levels typically below 12dB, beyond which both the BCH and convolutional coded systems with interleaving exhibit the same bit error rate performances. It can also be seen that the performances of coded OFDM with interleaving is superior compared to coded OFDM schemes without interleaving. Thus, the cumulative effect of coding and interleaving improves the overall bit error rate performance of OFDM substantially. The system can be modified by using more powerful codes like turbo codes or LDPC codes instead of convolutional and BCH codes.

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