Comparison of NBI suppression methods in OFDM systems

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Abstract— **In this paper, the effect of presence of narrowband interference (NBI) in orthogonal frequency division multiplexing (OFDM) system is investigated and analyzed. Wireless transmissions over unlicensed bands mostly face the undesirable effect of NBI. There is significant amount of performance degradation in such systems, thus NBI suppression techniques need to be employed. Some of the NBI suppression methods are frequency excision, frequency identification and cancellation, adaptive notch filtering, use of least mean square (LMS) algorithm, wavelet denoising and spread spectrum techniques. All these techniques improve the performance of an OFDM system with NBI to a different degree. In this work, a convolutionally encoded and interleaved FFT-OFDM and DWT-OFDM system with NBI and AWGN are tested for Quadrature Amplitude Modulation (QAM) and Differential Quadrature Phase Shift Keying (DQPSK) modulation. A gain of 99% is obtained for BER of 20dB over the case of no suppression with π/4-DQPSK modulated wavelet based OFDM for frequency domain identification and cancellation of NBI.**

Keywords—OFDM, NBI, QAM, DWT, DQPSK

I. INTRODUCTION

OFDM is a multicarrier modulation technique which meets the modern day demands of reliable and high data rate communication. Spectral efficiency and robustness against multipath fading are the major advantages of OFDM that has made it an attractive candidate to use in many applications. Some of the application areas where OFDM technology is made use are digital audio broadcasting (DAB), digital terrestrial video broadcasting (DVB-T), digital video broadcasting - satellite services to handhelds (DVB-SH) and 3GPP long term evolution (LTE) [1]. OFDM is also selected as air interface in wireless local area network (WLAN) and wireless metropolitan area network (WMAN) [2]. OFDM is considered in several standards such as IEEE802 11, IEEE802 16, IEEE802 20 and IEEE802 11 [3]. Besides all these advantages and applications of OFDM, it is also true that OFDM is sensitive to NBI.

NBI can be defined as the interference whose spectrum is far less than the signal transmission bandwidth occupied by the data [4]. NBI can be found in the new unlicensed frequency bands, e.g., the Industrial Scientific Medical (ISM) band, coming from systems such as Bluetooth or microwave ovens which interfere with OFDM based Wireless Local Area Networks (WLAN), like Hiperlan II. Other examples of NBI, typical for Digital Subscriber Line (DSL) communications, are strong Radio Frequency Interferences (RFI) from short-wave radio, which interfere with high speed DSL. Ineffective shielding of a cable network may also cause the ingress from external home electrical devices [5].

The performance degradation of an OFDM system in the presence of NBI is mainly due to the spectral leakage effect of NBI at the receiver before demodulation. This phenomenon will corrupt many subcarriers. NBI also causes non-linear distortion and many subcarriers close to interference frequency will suffer from serious SNR degradation [5]. Thus, NBI suppression in OFDM systems is of prime concern.

There are several techniques for NBI suppression in OFDM. The techniques which are employed in this paper are frequency excision, frequency identification and cancellation, adaptive narrowband filtering, LMS algorithm and spread spectrum techniques. Under spread spectrum techniques both direct sequence spread spectrum (DSSS) and frequency hop spread spectrum (FHSS) are tested with NBI. All these techniques are implemented in an OFDM system with convolution encoding, interleaving, pilot insertion and with an AWGN channel and additive NBI. NBI is modeled as single tone sinusoid. A comparison of all the techniques is made under both Fast Fourier Transform (FFT) based OFDM and Discrete Wavelet Transform (DWT) OFDM. The computer simulation shows that DWT-OFDM outperforms FFT-OFDM in most of the cases, due to the unique properties of wavelets.

The outline of this paper is organized as follows. In section II, DFT and DWT based OFDM system model is briefly introduced. Later, NBI suppression techniques used in OFDM is discussed in section III. Simulation results and its analysis are presented in section IV, and finally conclusions are given in section V.

II. SYSTEM MODEL

OFDM system has a flexible transform block both at the transmitter and receiver. Conventionally Discrete Fourier Transform (DFT) and Inverse DFT (IDFT) are used at the receiver and transmitter respectively. But they can be replaced with DWT or Discrete Cosine Transform (DCT) also. Among DFT, DWT and DCT based OFDM, the most popular are DFT and DWT based OFDM. Thus in the computer simulations given in section IV also, only DFT and DWT based OFDM are made use. In DFT based OFDM, DFT operation is implemented using Fast Fourier Transform (FFT). The block diagram of FFT-OFDM and DWT-OFDM are as shown in Fig. 1 and Fig. 2 respectively.

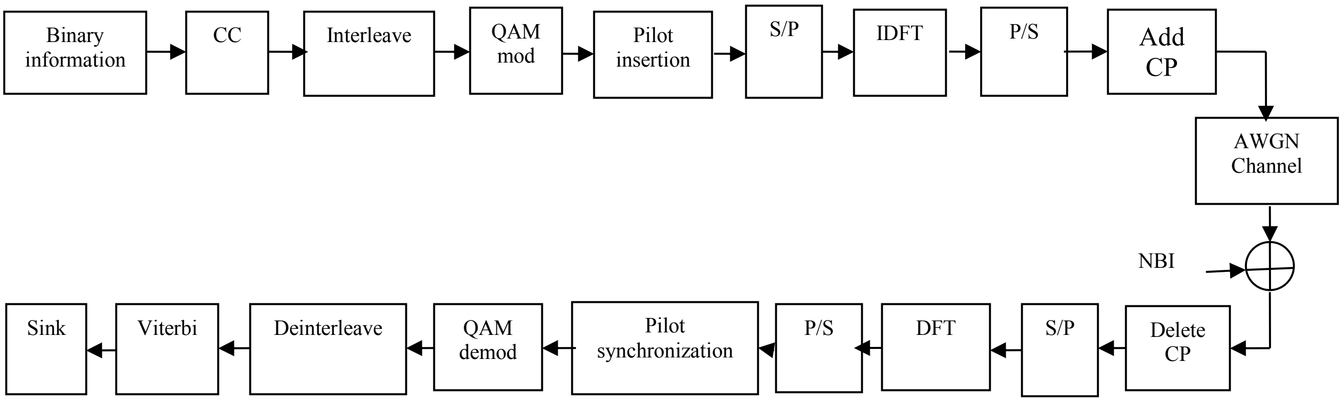

Fig. 1. Block diagram of FFT-OFDM

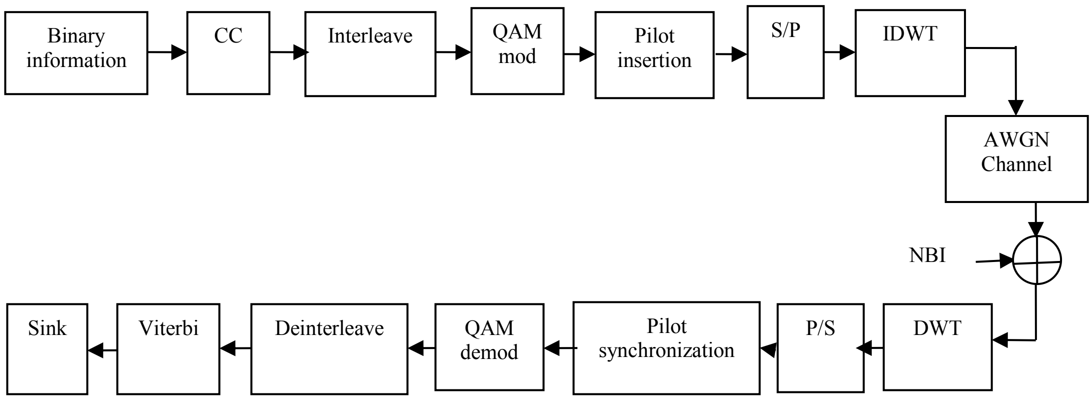

Fig. 2. Block diagram of DWT-OFDM

A. FFT-OFDM

In DFT based OFDM, the binary information is encoded and interleaved. Convolution coding (CC) is commonly used as it helps in error correction. Random interleaving is performed after coding. The coding-interleaving pair helps to combat burst errors. After interleaving, modulation is done using QAM. Later, channel estimation and synchronization is done using pilot tones. QAM is used here because it is efficient in conserving bandwidth. After modulation serial to parallel conversion is performed and symbols are mapped on to orthogonal subcarriers using IFFT (Inverse Fast Fourier Transform). The output of IFFT block in discrete time domain is given by equation (1).

(1)

Cyclic prefix (CP) which is nothing but repetition of the last few samples of OFDM symbol is appended to its beginning.

CP eliminates Inter-Symbol Interference (ISI), ICI (Inter-Carrier Interference) provided the CP duration is longer than channel delay spread.

After adding CP to OFDM signal, it is transmitted over the channel. The type of channel considered in this paper is a sum of AWGN and NBI.

At the receiver end, CP is removed. Serial to parallel conversion is done, and the FFT is applied to each parallel stream. The output after applying FFT is given as,

(2)

The parallel streams are again serialized and given as input to the QAM demodulator. The output of the demodulator is a binary stream, which is deinterleaved and decoded using Viterbi algorithm. The output of the decoder when compared with the original data stream depicts the amount of error the channel has introduced. One of the disadvantages of this FFT based OFDM is that the use of CP introduces overhead, which in turn reduces the bandwidth efficiency.

B. DWT-OFDM

The disadvantages in FFT based OFDM is overcome in DWT based OFDM. Here there is no need to add CP. Mainly DWT-OFDM allows the overlapping of subcarriers which leads to efficient use of bandwidth. Its improved spectral containment also helps in reducing Inter Carrier Interference

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(ICI) and Peak-to-average power ratio (PAPR). There is also a great reduction in side lobe levels.

The block diagram of DWT-OFDM resembles that of FFT-OFDM. The only difference is that DWT and IDWT is used in place of FFT and IFFT respectively and CP is not used.

The transmitted signal after IDWT operation in DWT-OFDM can be expressed as

(3)

The output of DWT at the receiver is given by,

(4)

Where is the wavelet function. DWT of a signal is a set of coefficients for m and k obtained as inner product of the signal and wavelet function [6].

III. NBI Suppression Techniques

The presence of NBI affects the performance of OFDM to a great extent. There are number of ways to suppress NBI among which frequency excision, frequency identification and cancellation, adaptive notch filtering, LMS algorithm and spread spectrum techniques are dealt in this section.

A. Frequency excision

Frequency excision is carried out in frequency domain. At the receiver the DFT output for N samples of OFDM signal is as shown in equation (5).

(5)

Where m is number of OFDM symbol, n is number of subcarrier of OFDM symbol, is digital base band signal sample at demodulator input for m. In the frequency domain, the NBI appears as a peak in the spectra. Interferences can be excised by comparing and limiting the magnitude of each frequency bin to a threshold [5].

The mean value of the amplitude of the frequency bins and its variance are computed as shown below and they are in turn used to compute the threshold for excision.

(6)

(7)

(8)

Where α is the scale factor and it is adjusted to maintain the threshold at some value of the noise floor. Each frequency bin is compared to the threshold and, if it exceeds the threshold, its value is held at the threshold. After applying IFFT, the signal is much less contaminated with narrow band interferences.

B. Frequency identification and cancellation

This method is also done after DFT operation at the receiver i.e. in frequency domain. The k^{th} complex sample at the input of OFDM receiver is given by,

(9)

Where is the complex output signal for the sample k at the transmitter, is impulse response of the channel, is Additive White Gaussian Noise (AWGN) for sample k, and is n^{th} complex single tone NBI for sample k. The narrow band interfering signal can be modeled as a complex sinusoidal tone.

(10)

(11)

In this approach, the NBI frequency is estimated by finding the maximum amplitude in the signal spectrum. A matrix is used to represent the interference.

(12)

(13)

(14)

The interference i_n is a column vector of size . Applying maximum likelihood algorithm, the solution is given by equation (11).

(15)

Where r is the input signal vector, is the estimated amplitude of n^{th} complex NBI. After estimating the amplitude, frequency and phase, NBI cancellation is carried out by subtracting the estimated signal from received signal.

(16)

Where is the input signal for the OFDM demodulator after NBI cancellation.

C. Adaptive narrowband filtering

Adaptive narrow band filtering assumes an NBI that occupies a much narrower frequency band with higher power spectral density compared with a wideband signal. This filtering is realized in frequency domain. It is linear filtering that is performed at the input of the demodulator. Here, Independent tuning of central frequency and bandwidth is possible.

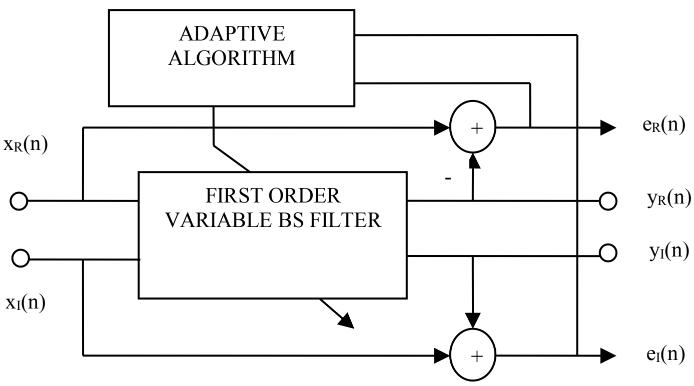

Fig. 3. Block diagram of BP/BS adaptive filter section

Fig. 3 shows the adaptive complex notch/bandstop system. The band-stop filter section is tuned at the NBI frequency, thus the signal represents the output of the filter which is in fact the NBI signal. Further, the NBI signal is subtracted by the input complex signal which is the additive sum of OFDM signal, NBI signal and AWGN. If perfect filtering is assumed, the result signal is supposed to be NBI-free OFDM signal.

D. LMS algorithm

LMS is most widely used algorithms in adaptive filtering. LMS algorithm is a type of adaptive algorithm known as stochastic gradient-based algorithms as it utilizes the gradient vector of the filter tap weights to converge on the optimal wiener solution. The iterative formulas of steepest descent method based on least mean square algorithm (LMS algorithm) are defined as follows

(17)

Where is the filter input, is filter output and are filter weights.

(18)

Where is the reference signal and is the error between and.

With each iteration of the LMS algorithm, the filter tap weights of the adaptive filter are updated according to the following formula.

(19)

LMS has several applications among which noise cancellation is one. The same logic can be made use in NBI cancellation also. In case of NBI suppression, LMS algorithm can be used to adaptively suppress a combination of AWGN and NBI. Here the sum of AWGN and NBI is treated as noise.

E. Spread spectrum techniques

Spread spectrum (SS) is a digital modulation technology and a technique based on principle of spreading a signal among a wide range of frequencies to prevent interference and signal interception. It increases the signal bandwidth beyond the minimum necessary for data transmission. SS has many capabilities like hiding the signal under the noise floor, its resistance to narrowband jamming and interference, reducing the effects of the ISI problem. The SS system inherently provides resistance to NBI by widening and suppressing the interference in the despreading process [7].

SS techniques are of two main types, namely DSSS and FHSS. Both of them require applying spreading process at the transmitter and despreading at the receiver. DSSS is the most popular SS technique where the data signal is multiplied by a pseudo random noise code (PN-code). PN code is either in polar or non-polar form, and it can be generated by one or more shift registers. The other type of SS is FHSS, where the carrier frequency is hopped according to the PN-code. Depending on the number of data bits transmitted within one hop, it is either categorized as slow-hop or fast-hop SS. Slow frequency hopping is where one or more data bits are transmitted within one frequency hop. An advantage for this kind is that the data can be detected coherently. A drawback is that if one frequency hop channel is jammed or subject to interference, one or more data bits will be lost. Thus in case of interference suppression, fast FHSS is preferred. In fast FHSS, data bit is divided over one or more frequency hops. An advantage for this type is that the diversity can be applied [8].

FHSS improves privacy. It is a powerful solution to avoid interference and multi-path fading. It decreases NBI, increases signal capacity, and improves the signal to noise ratio. The efficiency of bandwidth is high and it is difficult to intercept. Also this transmission can share a frequency band with many types of conventional transmissions with minimal interference.

Interference always exists in any wireless system. Bit error rate (BER) is highly important for the performance improvement of the communication systems. Every frequency channel due to interferences and fading shows different signal to noise ratio (SNR). The frequency channels that have stronger SNR become more suitable for the transmission [9]. Both DSSS and fast FHSS OFDM system with NBI are compared and the result is discussed under section IV.

F. Wavelet denoising

Wavelet is a waveform of effectively limited duration that has an average value of zero. Wavelets have several advantages like they can create subcarriers of different bandwidth and symbol length, they have the ability to arrange the time-frequency tiling in a manner that minimizes the channel disturbances, minimizes the effect of noise and interference on the signal. They can be used for data compression and mitigation of interferences.

Wavelet transform is used to characterize a signal both in time and frequency domain. It is scaled and shifted version of the time mother wavelet. The mother wavelet DWT is expressed as given in equation (20).

(20)

Where a and b are scaling and shifting factor, respectively. R is the wavelet space. Mother wavelet must satisfy the following condition

(21)

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Where is the Fourier Transform of mother wavelet function.

Wavelet thresholding is the signal estimation technique that exploits the capabilities of signal denoising. Thresholding method is categorized into two types such as hard thresholding and soft thresholding. The hard threshold function tends to have bigger variance and it is unstable [10].

(22)

However, soft thresholding function is much stable than hard thresholding and it tends to have a bigger bias due to the shrinkage of larger wavelet coefficients.

(23)

Where *w* is a wavelet coefficient; *t* is a value of threshold which is applied on the wavelet coefficients. There are four ways of selecting threshold, namely Heursure, Rigrsure, Sqtwolog and Minimaxi.

Wavelet denoising is used to extract useful signal from the signal contaminated with noise by reducing the noise component. In simple words, wavelet denoising is a process of reconstructing a signal from a noisy one using wavelets. The localizing property of wavelets and its ability to concentrate energy in a small number of wavelet dimensions, make wavelets suitable for denoising. During denoising, initially the input signal is decomposed using DWT. Decomposition is done with a suitable wavelet and decomposition level. Later, thresholding method and thresholding rule for quantization of wavelet coefficients are chosen. By applying threshold at each level of wavelet decomposition, the wavelet coefficients above the threshold are removed. Finally, the denoised signal is reconstructed without affecting any features of the signal of interest. The reconstruction can be done by performing the Inverse Discrete Wavelet Transform (IDWT) of various wavelet coefficients for each decomposition level [10].

IV. Simulation Results

In this section, the simulations carried out in MATLAB and results obtained are discussed. The OFDM system with the parameters given in Table I is used in the simulations.

TABLE I

Parameters	Specifications
Length of CP	16
Number of subcarriers/ no. of DFT or IDFT points	64
Rate of convolution encoder	1/2
Generator polynomials used in CC	[133], [171]
Modulation type	16-QAM, $\pi/4$ DQPSK
Channel model	AWGN+NBI
Type of wavelet used in case of DWT-OFDM	haar, db4
Decoding algorithm	Viterbi

A. Comparison between DFT-OFDM, DCT-OFDM and DWT-OFDM

The BER versus SNR curves obtained for DFT, DCT and DWT based OFDM is as shown in Fig. 4.

From the Fig. 4 it implies that the performance of DFT-OFDM and DCT-OFDM are comparable. Whereas, an improvement of approximately 3dB is obtained in case of DWT-OFDM compared to DFT-OFDM. In conventional OFDM systems DFT operation is made use than DCT. Thus further simulations regarding NBI cancellation are done for only DFT-OFDM and DWT-OFDM.

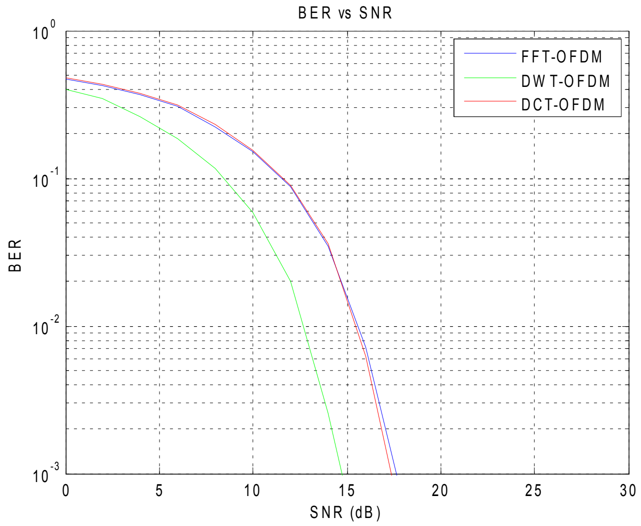

Fig. 4. Comparison of BER curves of DFT, DCT and DWT based OFDM system.

B. NBI suppression in FFT-OFDM using 16-QAM

In case of FFT OFDM, the performance improvement caused by different NBI suppression techniques can be observed in Fig. 5. The gain obtained by the use of wavelet denoising, adaptive notch filtering, frequency excision, LMS and frequency identification and cancellation in FFT-OFDM with NBI are 8.95%, 28.19%, 28.95%, 36% and 96.746% respectively. The gain is calculated with reference to the case of no NBI suppression. The comparison of all methods is done by considering the BER values obtained for a fixed SNR of 20dB, and the plot clearly illustrates that frequency identification and cancellation outperforms all other methods.

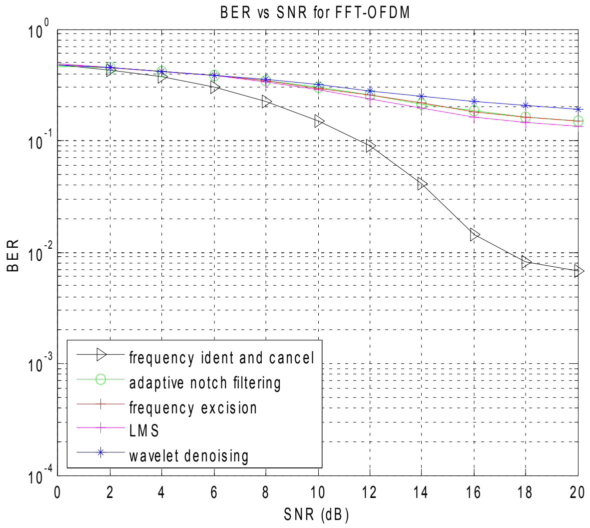

Fig. 5. Comparison of different NBI suppression techniques in FFT-OFDM

The effect of using FHSS and DSSS in FFT-OFDM with NBI offers gains of 97% and 56.95% respectively. It can be clearly seen from the Fig. 6 that a lower BER is obtained using FHSS. This is because in case of FHSS, when NBI is detected at a particular subcarrier, then a frequency hop is made randomly to another subcarrier frequency, due to which the adverse effect of NBI is avoided.

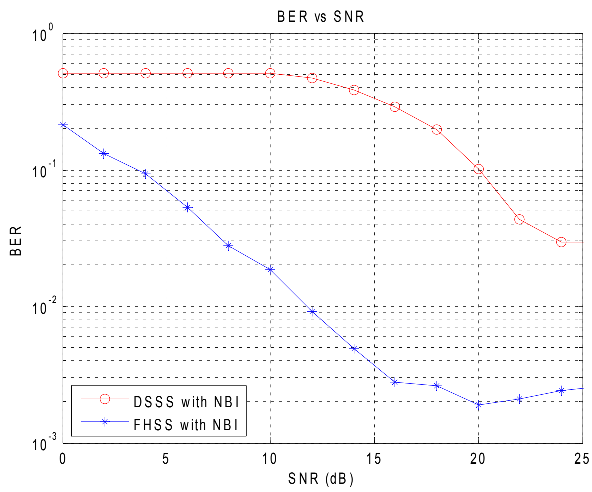

Fig. 6. Comparison of DSSS and FHSS OFDM system with NBI

C. *NBI suppression in DWT-OFDM using 16-QAM*

In DWT-OFDM, IDWT operation is done at the transmitter end and DWT at the receiver end. For both IDWT and DWT, the wavelet used is 'haar'. This is because compared to all other wavelets the least BER is obtained for haar. Wavelet denoising, adaptive notch filtering, frequency excision, LMS and frequency identification and cancellation provides a gain of 15.9%, 16.857%, 65.2%, 67.638% and 98.72% respectively in DWT-OFDM with NBI. Same as in case of FFT-OFDM, the greatest gain in performance is obtained for frequency identification and cancellation of NBI. When a comparison of gains obtained for different NBI suppression techniques for an SNR of 20dB is made between FFT-OFDM and DWT-OFDM, it can be seen that in most of the cases, DWT-OFDM outperforms FFT-OFDM. The same can be viewed in Fig. 7.

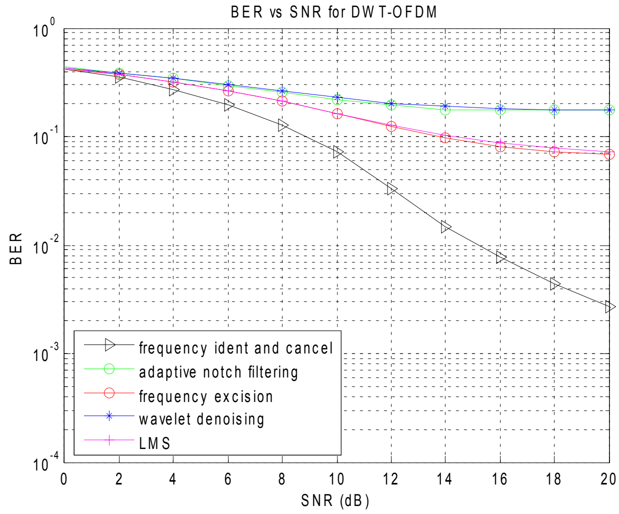

Fig. 7. Comparison of different NBI suppression techniques in DWT-OFDM

Applying DSSS and FHSS techniques in wavelet based OFDM with NBI shows a positive improvement in the performance. They offer gains of 98% and 90.43% respectively. Especially it can be seen in Fig. 8 that there is a huge improvement in the performance of DSSS-OFDM.

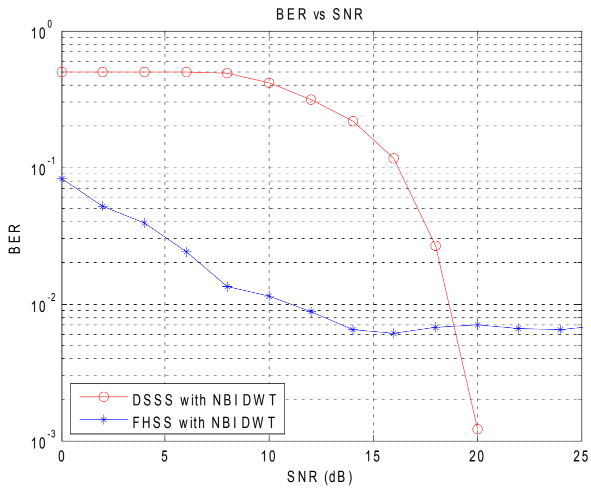

Fig. 8. Comparison of DSSS and FHSS OFDM system with NBI

D. *NBI suppression using DQPSK modulation*

The use of differential modulation schemes in OFDM systems allows low-cost receiver designs without channel estimation. An OFDM system with $\pi/4$-DQPSK modulation has been adopted in the DAB standard [11]. Though QAM is

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the most popular modulation technique used in OFDM, if π/4-DQPSK is used in place of QAM then an improvement in BER performance of OFDM is observed. The same can be seen in Fig. 9.

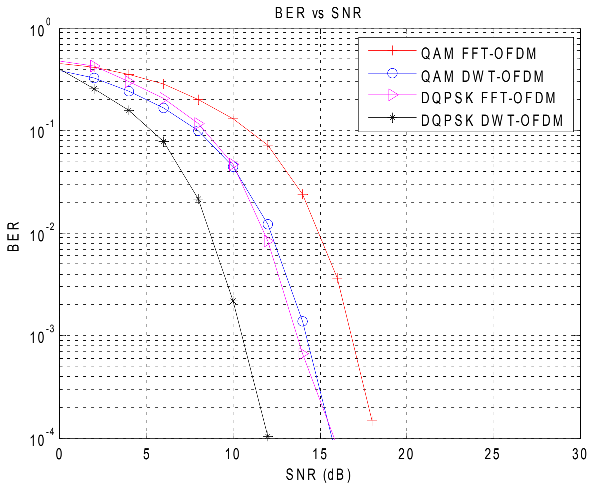

Fig. 9 Comparison of QAM and DQPSK in FFT-OFDM and DWT-OFDM

It can be observed from the plot that there is approximately 3dB improvement in the performance of DQPSK-OFDM compared to QAM-OFDM may it be the use of FFT or DWT in OFDM.

When the NBI suppression techniques are used in DQPSK modulated FFT-OFDM they provide gains of 40%, 42.476%, 47.428%, 73.152% and 97.906%. Maximum gain is obtained for frequency identification and cancellation. This is because the position of occurrence and transition bandwidth of NBI can be accurately estimated in frequency domain. Once NBI is estimated, they can be reconstructed and cancelled in frequency domain easily. Minimum gain is obtained in case of wavelet denoising. This is obvious, because denoising only helps in reducing the background noise. The behavior of NBI suppression techniques in DQPSK-FFT-OFDM is as shown in Fig. 10.

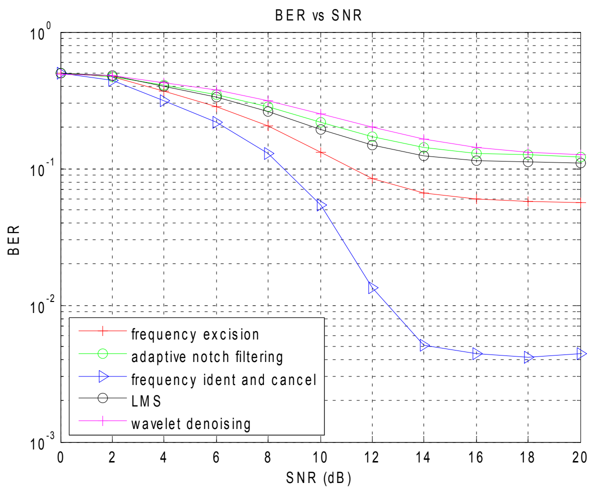

Fig. 10. Comparison of NBI suppression techniques in DQPSK-FFT-OFDM.

The use of NBI suppression in DQPSK-DWT-OFDM shows an even better execution. It is evident from Fig. 11 that wavelet denoising, adaptive filtering, frequency excision and frequency identification and cancellation techniques offers gains of 18.238%, 30%, 94.12% and 99.9% respectively over the case of no suppression.

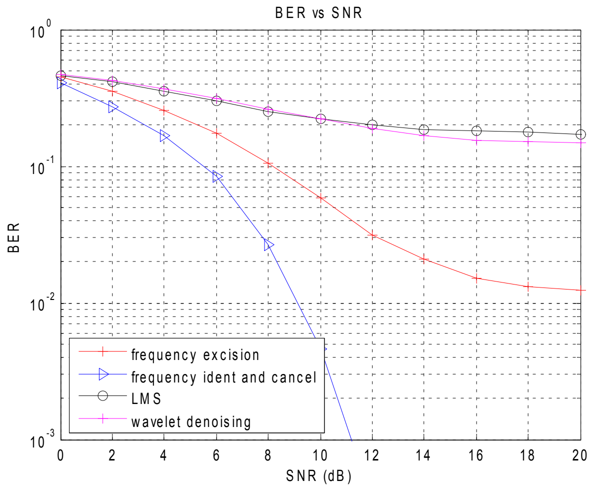

Fig. 11 Comparison of NBI suppression techniques in DQPSK-DWT-OFDM.

V. Conclusion

In this paper performance of OFDM system with NBI has been examined and results shows that frequency domain identification and cancellation technique for NBI suppression is a more suitable choice as it provides a gain of around 99% over the case of no NBI suppression. In addition, the use of NBI suppression techniques in wavelet based OFDM outperforms that in FFT based OFDM by 3dB SNR with respect to a fixed BER. Regarding the modulation type, π/4 DQPSK give better results than QAM in the case of NBI suppression.

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