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Out of Band Interference Reduction in OFDM Based Systems

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Abstract:*In this paper, various techniques for removing out of band interference in Orthogonal Frequency Division Multiplexing (OFDM) systems have been compared to produce lower levels of interference. Out of band interference in OFDM is caused due to the sidelobes present in the spectrum of an OFDM symbol, which causes interference in the adjacent sub-carriers. The techniques which have been compared include Carrier Nulling, Windowing & Active Interference Cancellation (AIC). All these techniques are incorporated into a MATLAB code. As an improvisation, the number of AIC tones was varied, thus producing different interference levels in each case. However, as the number of AIC tones was increased, optimisation technique was incorporated to bring the power to a threshold level.*

Keywords: *Orthogonal Frequency Division Multiplexing (OFDM), Out of Band (OOB), Active Interference Cancellation (AIC), Raised Cosine (RC), Inter-carrier Interference (ICI).*

I. Introduction

Out of band (OOB) interference is a major limitation of an OFDM system. It is caused due to the roll off of the sidelobes of one sub-carrier into adjacent sub-carriers resulting in Inter-carrier interference, thus causing a reduced system performance. The sidelobes are produced as a result of symbol truncation in the time domain causing interference to the primary users in neighbouring band. This interference results in the wastage of the frequency spectrum. In order to reduce the interference into the adjacent frequency bands, the sidelobes of the OFDM symbol need to be supressed. Various techniques have been implemented to suppress the sidelobes of an OFDM symbol [1] [2]. These techniques are applied in both time as well as frequency domain. However, some of these techniques result in a reduced throughput in the overall system. A technique of inserting cancellation carriers has been used [3]. In this method, few cancellation carriers are inserted on either side of the OFDM spectrum with pre-computed weights. The weights are calculated by selecting an optimization region, which is the portion of the adjacent RF spectrum over which the sidelobes need to be repressed, and finding an optimal solution. The optimization is formulated as a linear least squares problem, solved using a singular value decomposition technique. Another technique exploits the fact that different symbol sequences constitute different sidelobe power levels, and hence proposes transmitting the symbol sequence with the least sidelobe power levels instead of the generated symbol sequence [4].Windowing and Adaptive symbol transition are implemented in time domain [5]. In windowing, the overall spectrum of OFDM is to be concerned. Passing an OFDM baseband signal through the windowing block will accomplish the task of removing out of band components. Hence, it can be reflected as a shaping filter also. Windowing helps in conniving next transmission bandwidth closer to the previous one and preserving the orthogonality. Both the methods result in reduced throughput due to the extension of symbol in the time domain. In frequency domain, tones nulling can be utilized but this is not satisfactory for interference suppression. Further suppression can be achieved by applying active interference cancellation(AIC) which introduces AIC edge tones to annul the side lobe interference [6]. One of the techniques to reduce the out of band interference in an OFDM symbol is Carrier nulling. In this scheme, a particular set of tones are turned off in order to reduce the interference in the victim band under consideration. The sub-carriers which are turned off are known as null carriers. This technique produces a lower level of interference but results in the loss or wastage of frequency spectrum by nulling a large set of sub-carriers. Another technique used for Out of band interference reduction is known as Raised Cosine windowing. In this scheme, each OFDM signal is extended by TW samples at both ends to smooth the transitions between successive symbols. This is done mainly to improve the out of band spectrum and reduce the interference to adjacent channels. This spectral shaping technique is applied in time domain after adding the Guard interval (GI) [7].The Raised Cosine function is applied in time domain for OFDM systems and in frequency domain for single carrier systems transmission systems. One of the most efficient techniques for sidelobe suppression in an OFDM system is that of Active Interference Cancellation.In this technique, the interference in the equivalent baseband OFDM signal is considered. Instead of turning off a large number of tones as is the case with carrier nulling, special pair/s of tones are defined at the edge of the interference band also known as victim band, so that these tones can sufficiently cancel the interference in the band. The value of these tones can be determined arbitrarily without affecting the orthogonality of the corresponding sub-carriers of the OFDM system. These special tones used at the edge of the interference band are known as Active Interference Cancellation (AIC) Tones. Active Interference Cancellation is a frequency domain technique. However, when the number of AIC tones is increased, it results in a peak overshoot resulting in high power consumption. In order to restore the power spectral density to threshold level, a convex optimisation technique is used which optimises the tones to produce compromising power levels. An improvisation to the AIC technique is provided by varying the number of AIC tones and providing the required optimisation for higher number of AIC tones.More methods such as spectral precoding, subcarrier weighting (SW), multiply data carriers with some pre computed weighting factor to decrease sidelobes [8]. These techniques have certain limitations which result in a reduced system performance.

II. System Analysis

OFDM is leading the technological sector into a new era of digital transmission and is becoming the favourite modulation technique worldwide. It is the most reliable technique for high data rates and maximum spectral efficiency due to the orthogonality of the corresponding sub-carriers. In near future, OFDM systems can support the data rates as high as 100 Mbps [9]. However it faces a huge limitation due to the roll off of the sidelobes of an OFDM symbol into the adjacent frequency bands. To overcome this limitation, various techniques have been analysed which include Carrier Nulling, Raised Cosine (RC) Windowing and Active Interference cancellation. Main focus has been concerned on Active Interference Cancellation which reduces the interference to significant levels. An improvisation to AIC scheme has been provided by varying the pairs of AIC tones and producing lower levels of interference correspondingly.

In carrier nulling technique, a particular set of tones is turned off in order to reduce the out of band interference in the victim band. An OFDM system of 128 sub-carriers is modelled such that certain sub-carriers are kept as ones and certain set of sub-carriers are kept as zeros [10] [11]. The sub-carriers which are kept as zeros are considered to be null carriers. In our case, we have nulled 6 out of 128 sub-carriers and the rest of the sub-carriers are turned on. This technique reduces the interference levels but results in the loss of spectrum due to the wastage of sub-carriers which are turned off.

In Raised Cosine (RC) windowing technique, each OFDM symbol is extended by TW samples at both ends to smooth the transitions between successive symbols. This is done mainly to improve the out of band spectrum and reduce the interference to adjacent channels. This spectral shaping technique is applied in time domain after adding the Guard interval (GI). Windowing extension is 16 samples. Cyclic prefix (CP) length is 16 samples, so the first 16 samples are copied and appended to the end of the OFDM symbol. The last 32 samples (last samples before the previous step) are copied which are then added to the start of the symbol. Then the left and right windows are applied to the first and last 16 samples respectively. Similarly, this is done for every OFDM symbol. With this, each symbol is extended by 32 samples. However, each symbol is should only be extended by 16 samples in order for them to overlap. Hence, the last W samples should be added to the first W samples of the successive symbol. This means that each symbol is extended effectively. The extension can be given as:

$$y(n) = \begin{cases} x(n+N) & \text{for} - G - W \le n \le -1 \\ x(n) & \text{for } 0 \le n \le n-1 \\ x(n-N) & \text{for } N \le n \le N+W-1 \end{cases}$$

In the next step, the Raised Cosine function is applied to the first and last W samples of y(n) respectively. The Windowing function w(n) is given as:

$$w(n) = \begin{cases} \cos^2\left(\frac{N+G+1}{W-1} * \frac{\pi}{2}\right) & \text{for} - G - W \le n \le -G-1 \\ 1 & \text{for} - G \le n \le N-1 \\ \cos^2\left(\frac{n-N}{W-1} * \frac{\pi}{2}\right) & \text{for } N \le n \le N+W-1 \\ 0 & \text{otherwise} \end{cases}$$

w(n) is similar but not equal to the transfer function of a Raised Cosine Filter often used as impulse shaper in single carrier transmission system.

Finally, the OFDM symbol including GI and spectral shaping is calculated by:

$$z(n) = w(n) * y(n)$$

The OFDM symbol is multiplied by a Raised Cosine window w(n) to more quickly reduce the power of out of band sub-carriers. The OFDM symbol is then added to the output of the previous OFDM symbol with a delay of T_S such that there is an overlap region of βT_s where β is the roll off factor of the RC window.

One of the most important sidelobe suppression techniques is the Active Interference Cancellation (AIC). In this scheme, a special set of tones known as AIC tones are added at the edge of the victim band or the interference bans. The value of AIC tones is determined arbitrarily. Here, the transmitted OFDM signal is given by:

$$x(n) = \sum_{k=0}^{127} X(k) \exp j2\pi \left(\frac{nk}{128}\right)$$

where X(k)is the information data and k=0,1,2,…,127. To calculate the interference in between the tone frequencies, we up-sample the corresponding frequency spectrum (e.g by 8) which is given by:

$$\mathrm{Y(l)} = \frac{1}{128} \sum_{\mathrm{k}=0}^{127} \mathrm{X(k)P(l,k)}$$

where P(n,l) is the transmission kernel.

In carrier nulling technique, we used to turn off a large number of tones which resulted in a reduced throughput and loss of data. Now, instead of turning off a large number of tones, a special pair of tones at the edge of the victim/interference band is defined. It can further be found out that these pair of tones can cancel the interference in the band under consideration quite effectively. The value of these tones can be determined arbitrarily, thus maintaining the orthogonality of the various sub-carriers. A set of 3 tones are selected as in-band tones or what we can call as the victim band. On the both edges of these tones are kept AIC tones. Thus 3 in-band tones are surrounded on the edges by a pair of AIC tones. In total, 5 tones are used to cancel the interference in the victim band. In-band tones do not carry much importance and can be kept zero. The number of AIC tones can be varied in order to calculate the different levels of interference. Interference to the victim band is evaluated at 8 times or much higher finer frequencies, denoted by a vector d_1. d(1), d(4) and d(8) correspond to the 3 in-band tones respectively. The vector d_1 is given as:

$$\mathrm{d_1 = pg}$$

where g is the vector of information data tones, with the 3 in-band tones turned off. To cancel the interference in the band, we need to generate negative of the interference signal using the 3 in-band tones. If we set all the information tones(X) to zero except the 3 in-band tones, we need to solve the following equation:

$$\mathrm{p_1 h = -d_1}$$

where h is the column vector of the in-band tones and p_1 is the small kernel derived from p by limiting the index according to h and d_1

Table 1 Dimensions of vectors

S.no	Vector	Dimensions
1.	G	128×1, with active tones off
2.	P	9×128
3.	d_1	9×1
4.	H	5×1
5.	p_1	9×5

Here h is our desired tone values.

$$\mathrm{p(l,k)} = \sum_{n=0}^{127} \exp[\mathrm{j2\pi}\left(\frac{\mathrm{n}}{128}\right)\mathrm{k} - \left(\frac{\mathrm{l}}{4}\right)]$$

After matrix minimization of p, we have

$$\mathrm{h = \|p_1 h + d_1\|^2}$$

which leads to

$$\mathrm{h = -(p_1^T p_1)^{-1} p_1^T d_1 = -W_1 d_1}$$

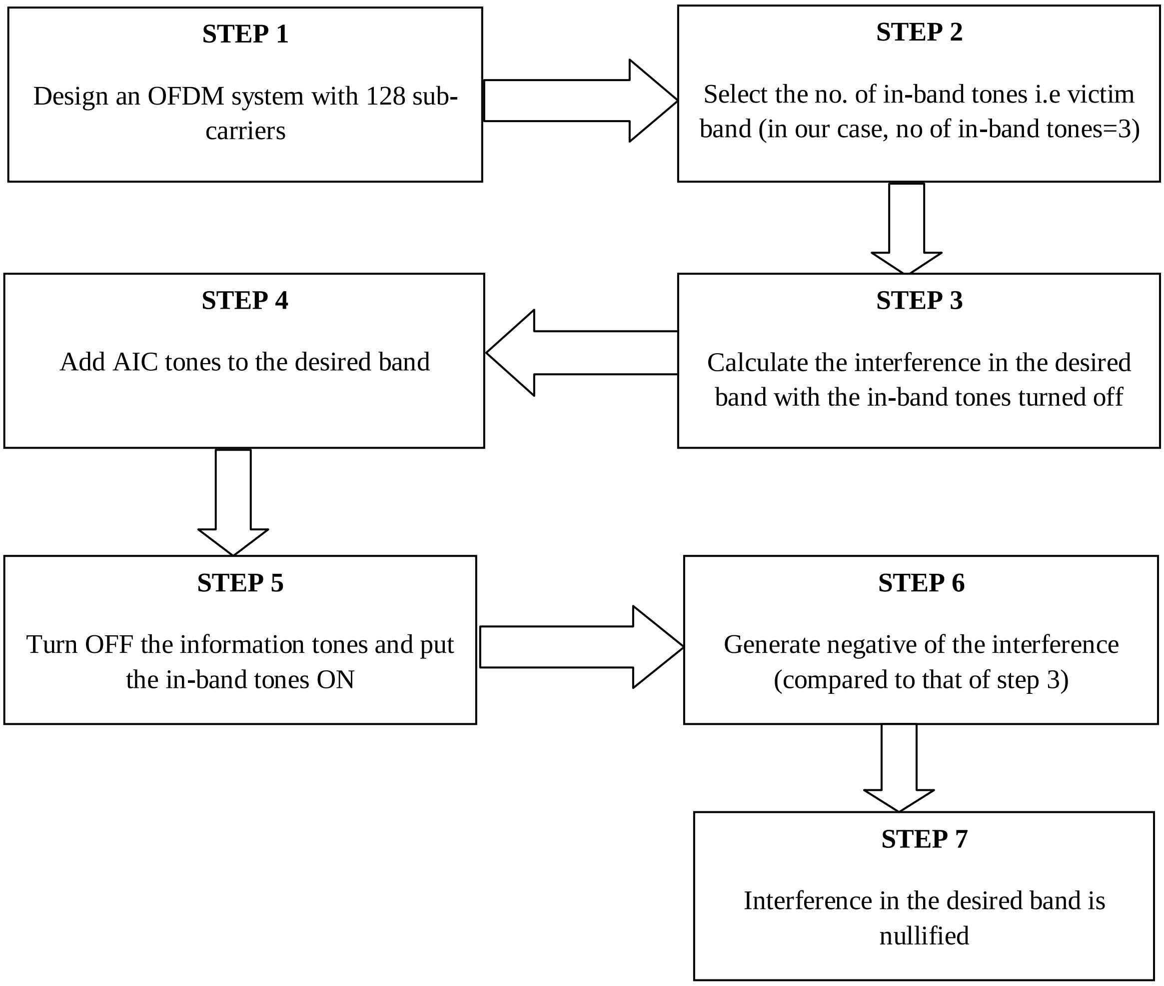
W_1 is pre-computable because the interference band location is pre-defined. From the above equations, we have

$$\mathrm{h = -W_1 pg = \ -W_2 g}$$

where W_2 is a pre-computable 5×128 matrix.

III. Algorithm for Active Interference Cancellation

The step by step algorithm for Active Interference Cancellation technique can be given as:



IV. Results and Discussion

Interference levels in different Out of Band interference reduction techniques can be shown as:

4.1 Carrier Nulling

The effect of this sub-carrier nulling can be studied through a Simulink model whose results can be shown as under:

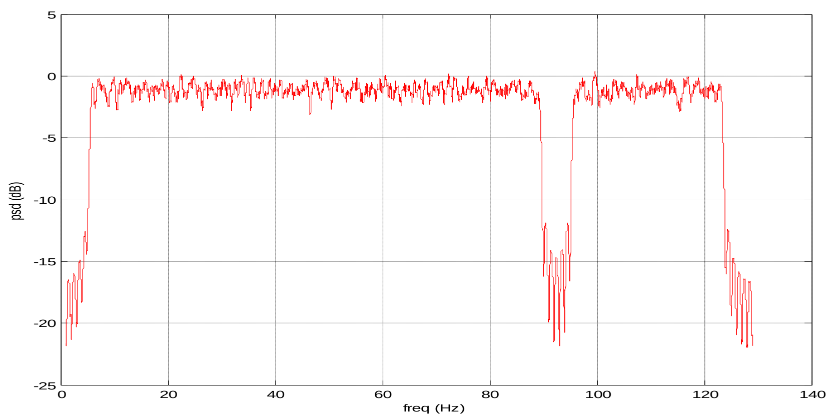


Fig.1 Carrier Nulling

4.2 Raised Cosine Windowing

Raised Cosine windowing is applied to an OFDM system and is incorporated into MATLAB to find the out of band interference levels caused due to the sidelobes present in the spectrum. These interference levels are compared with the previously incorporated conventional OFDM. The plot in red depicts the conventional OFDM and the one in green is that of OFDM with Raised Cosine Windowing.

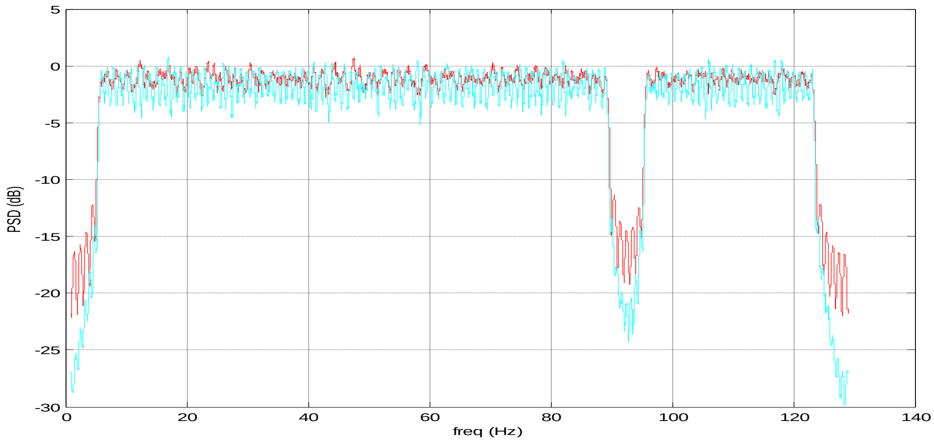


Fig. 2 Raised Cosine (RC) Windowing

From Fig. 2, it can be inferred that the interference levels have reduced in case of raised cosine (RC) windowing technique compared to that of conventional OFDM by a notch of 6dB**.**

4.3 Active Interference Cancellation (AIC)

Previous Results

In the previous results, the interference suppression for the AIC technique without optimization gives an interference suppression of 30dB, 35dB and 40 dB for 2, 3 and 4 bits in AIC tones. This technique is done without optimisation. However peaks begin to appear after increasing the bits in the AIC tones. These results can be shown as under:

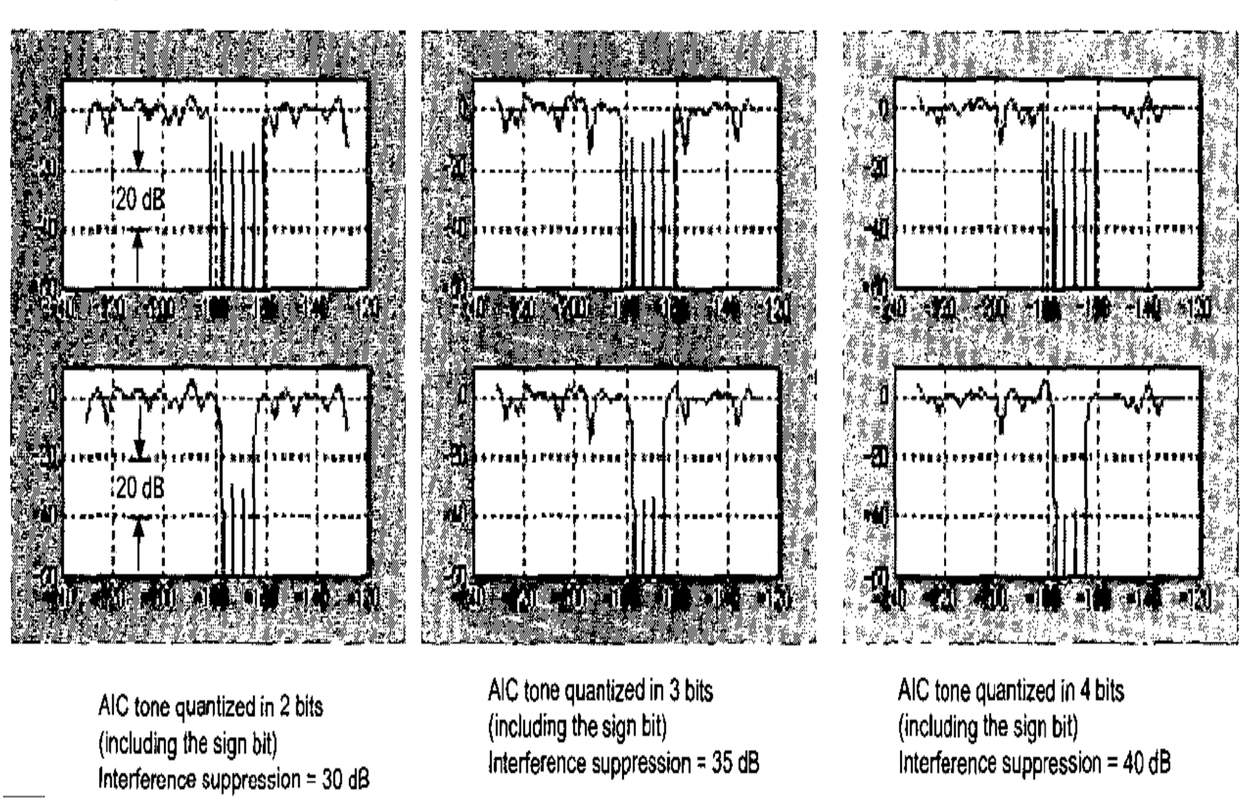


Fig. 3 Interference Suppression [6]

4.4 Active Interference Cancellation (AIC) (without Optimization)

Now, incorporating the AIC tones into the OFDM system and computing the interference levels in MATLAB, we get the following results.

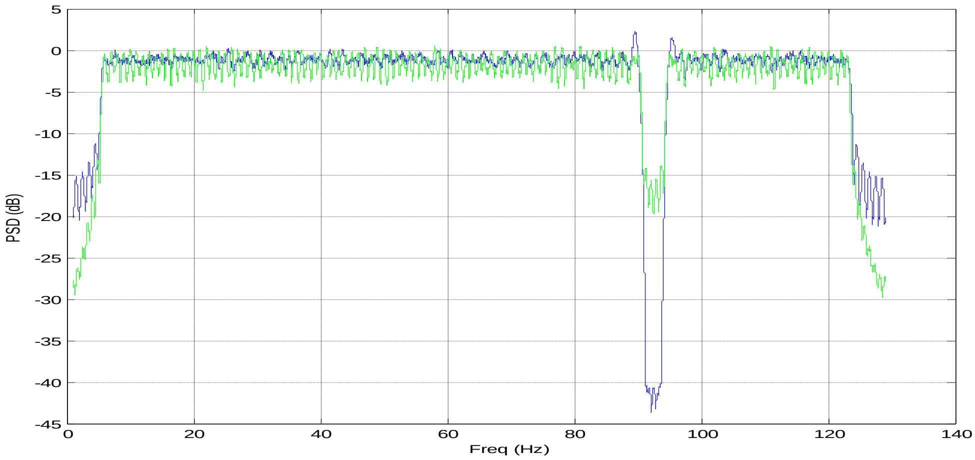


Fig. 4OFDM system with 2 AIC tones (without optimisation)

The plot in Fig. 4 shows the comparison between conventional OFDM (in Green) and the OFDM with Active Interference Cancellation tones (in Blue). Hence, it can be seen that the interference levels have reduced considerably by a notch of 24dB when compared with the conventional OFDM. Thus the AIC technique used to reduce the Out of Band Interference levels in an OFDM is a very useful technique.

In the above inferred result the number of pairs of AIC tones used is 1, that is

n_aic=1

So, total AIC edge tones used = 2*n_aic = 2*1 = 2

These AIC edge tones can be varied to produce different levels of interference. Depending on the number of edge tones used, the interference is produced accordingly.

In another case, let us take

n_aic = 2

which means the total number of edge tones used is 4, 2 on each edge of the victim band(3 in-band tones).

The interference levels for this case can be shown as:

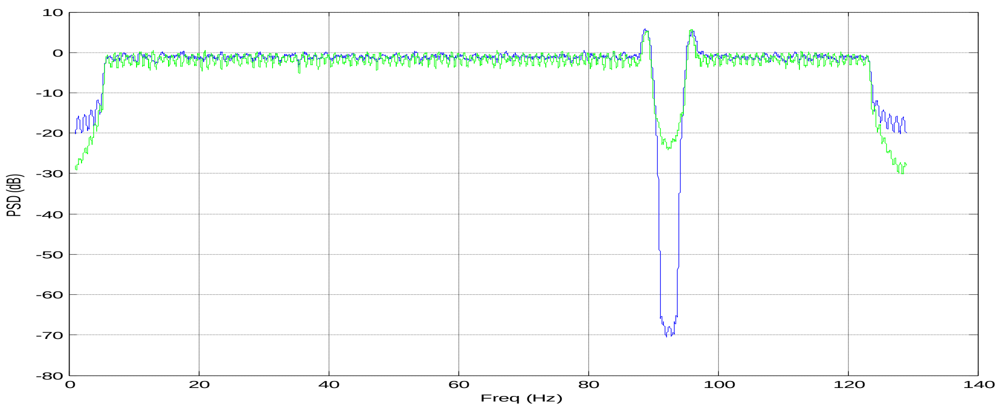


Fig. 5OFDM system with 4 AIC tones (without optimisation**)**

From Fig. 5, it is clear that the interference level has decreased considerably compared to conventional OFDM, by a notch of around 50dB. However, as the number of edge tones is increased, Peaks begin to appear above zero level as can be seen from the above figure. These peaks result in high levels of power consumption because they shoot above the zero level which in turn results in system degradation.

When 6 edge tones are used, i.e

n_aic=3

the interference levels and the position of peaks for this case can be shown as:

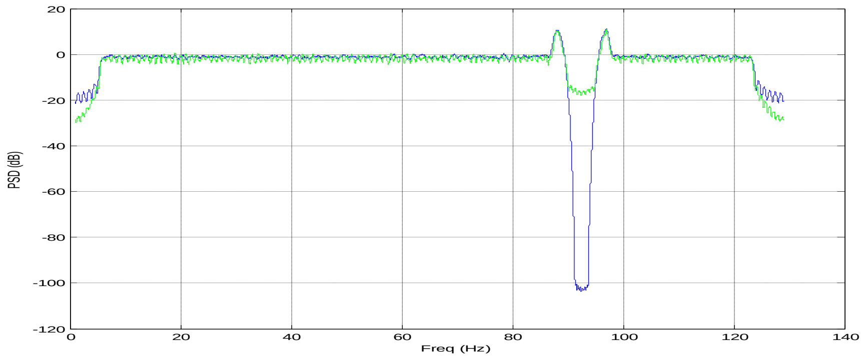


Fig. 6OFDM system with 6 AIC tones (without optimisation)

From Fig. 6, it can be concluded that although the interference levels drop considerably but the system power consumption is compromised due to the overshoot of peaks above the zero level.

In order to overcome this peak overshoot above the zero level, a Convex Optimization system is used which restricts the peaks below the zero level to maintain the power consumption of an OFDM system at tolerable level.

4.5 Active Interference Cancellation with Optimization

When the optimization technique is incorporated in an OFDM system with AIC tones, the interference levels can be given as follows:
For a system with 2 edge tones, i.e
n_aic= 1
the interference level compared with that of conventional OFDM can be shown as under:

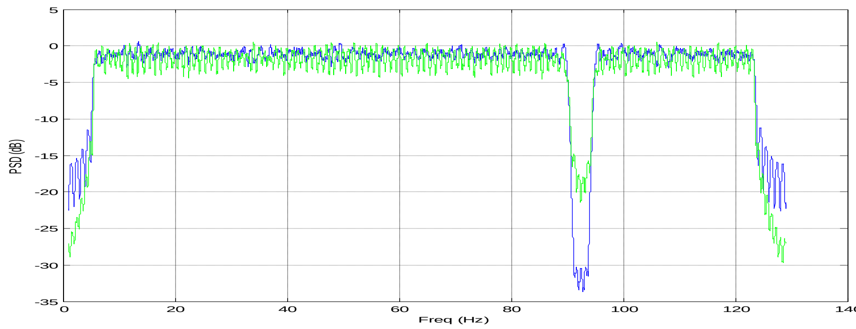


Fig. 7OFDM system with 2 AIC tones (with optimisation)

When Fig. 7 (2 AIC tones with optimization) is compared with Fig. 4 (2 AIC tones without optimization), it can be seen that he interference levels have increased slightly under a notch of around 8dB but the peak of the power spectral density has been restrained within optimum(zero) levels. Hence, the OFDM system using AIC with optimization is more reliable than the one without optimization.
Similarly, for different number of AIC edge tones, the interference levels with optimization can be given as:
When 4 AIC edge tones are used, i.e
n_aic = 2, the interference levels can be shown as:

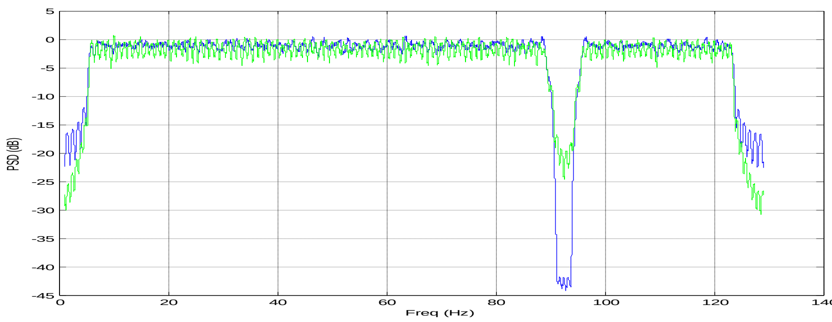


Fig. 8OFDM system with 4 AIC tones (with optimisation)

The interference has somewhat increased by a notch of 25 dB with peaks below the threshold level. Now, when 6 AIC edge tones are used, i.e
n_aic=3,the interference pattern for this case can be given as:

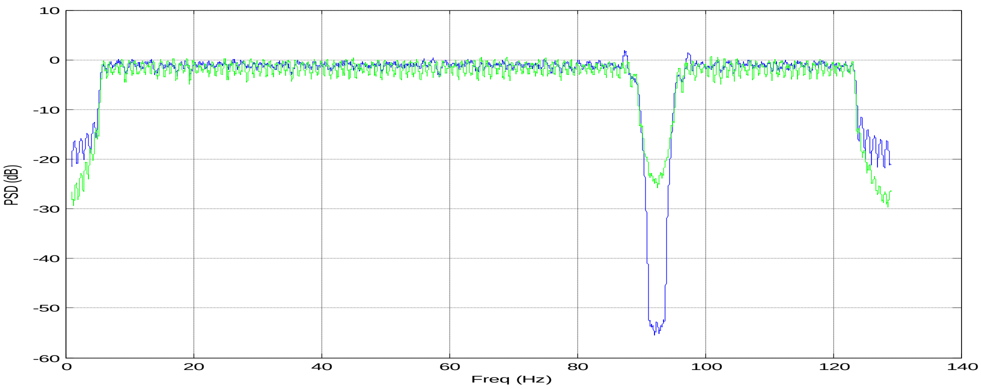


Fig. 9OFDM system with 6 AIC tones (with optimization)

From the above figure, it can be seen that as the number of AIC edge tones is increased beyond 6 (i.e n_aic=3), peaks start appearing again above the threshold level even with optimization.
Thus, when we extend the number of AIC edge tones to 8, i.e
n_aic=4
The interference pattern for this case can be shown as under:

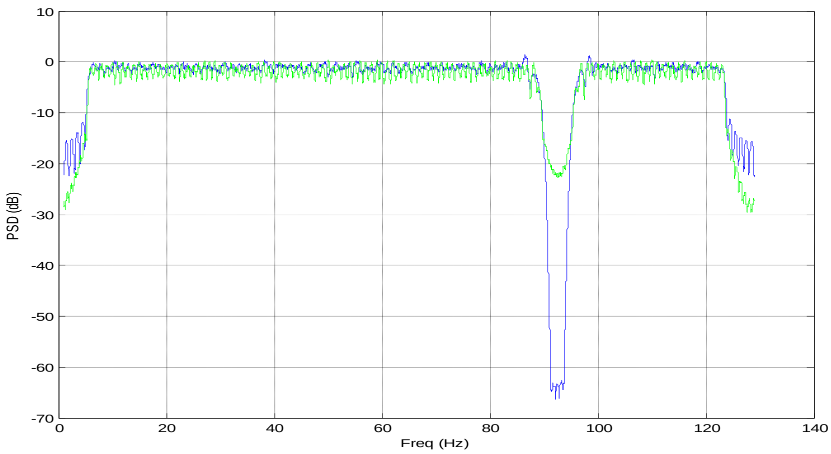


Fig. 10OFDM system with 8 AIC tones (with optimisation)

Table 2 AIC with optimisation

No. of AIC tones	n_aic	Interference reduction	Position of peaks
2	1	**20dB**	**1Db**
4	2	**48dB**	**6dB**
6	3	**81dB**	**10dB**

Table 3 AIC without optimisation

No. of AIC tones	n_aic	Interference reduction	Position of peaks
2	1	**12dB**	0dB
4	2	**28dB**	0dB
6	3	**32dB**	**1.5dB**
8	4	**40dB**	0dB

V. Conclusion

Once all the OOB suppression designs are based on the same unified system, it becomes very convenient for us to judge whether different schemes are suitable or not if they are both implemented simultaneously in one system and then perform the combining designs for those compatible schemes.In this paper we summarized the review of OFDM interference reduction .We mention various interference reduction techniques with their effect on the important parameters of OFDM. So to reduce the interference between subcarriers, we have to keep different parameters in mind before going ahead with the interference reduction.The Active Interference Cancellation (AIC) technique presented here works on the benefits of frequency domain signal processing and does not involve nulling of a large number of tones of an OFDM symbol. Only few tones are added, (as an improvisation, the number of tones have been varied) at the edge of the interference band whose values are determined arbitrarily. These tones are used to reduce the levels of interference produced by the out of band spectrum. By using this technique, the interference levels are reduced significantly in the frequency domain.

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