MITIGATION OF NARROWBAND INTERFERENCE IN DIFFERENTIALLY MODULATED COMMUNICATION SYSTEMS

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ABSTRACT

Integration of RF/Analog and digital into a single chip can result in the coupling of digital spurs in the analog front end of a communication systems and can severely degrade the receiver performance. In this paper, we propose a novel receiver architecture of a notch filter together with the feedback filter (FBF) of the decision feedback equalizer (DFE) to mitigate the impact of narrowband interference in differentially modulated communication systems without enhancing the inter-symbol interference (ISI). The proposed solution can be adapted to receiver architectures that employ either coherent or non-coherent demodulation of differentially modulated systems. Simulation results demonstrating the spur mitigation capability of the proposed solution is presented.

***Index Terms*—** Spur mitigation,narrowband interference, differential modulation, DPSK, decision feedback

1. INTRODUCTION

In wireless technologies there is a significant need to reduce area of the system on chip (SoC) to enable design of system solutions with small footprint which find their way into cellphones. Integration of different systems on to a single die and migration from one process node to another enable us to design area efficient systems. However, reducing die size increases the RF/analog coupling between various blocks causing spurious emissions (spurs) in different bands. For example, harmonics of the reference clock can couple back in to the receive path and degrade sensitivity performance of the system. In fact, the sensitivity performance of the receiver can degrade by as much as 8-10 dB in the presence of the spurs.

One possible way to reduce the spurs is to do careful floor-planning in the layout and shield the sensitive blocks using guard rings[2]. For example, to reduce the coupling of the reference clock spurs, the slicer can be shielded by guard rings. The clock slicer and the receive LNA can also be well separated in the layout. But with the reducing die sizes it becomes extremely difficult to avoid spurs just by doing floor-planning. The effectiveness of the guard rings also becomes less as the transistor sizes reduce with the process migration.

As the analog solutions are not completely effective, active interference cancellation by adaptive filters in digital baseband solution is a possible method to mitigate the impact of the spurs[3]. The limitation of this scheme is that the gain changes in the receiver analog chain by automatic gain control (AGC) can significantly change the amplitude and phase of the spur. The spur amplitude can also be a highly time-varying depending on the number of gates toggling at any instant and the tracking performance of the adaptive algorithms can be poor if the interferer strength is lower than that of the desired signal.

A notch filter in digital domain is another viable option to suppress the spur. However, the inclusion of notch filter to suppress the spur introduces ISI[1]. The impact of ISI can be partially mitigated by the forward error correction coding in the system. However, for an uncoded system, the receiver performance can severely degrade if the ISI is not removed. In [4] and [5] a notch filter is designed with a one or two-sided transversal filter and a DFE is used to remove the ISI. These references study the performance of this architecture for narrowband interference rejection in coherent demodulation of BPSK and QPSK systems.

In this paper we consider the case of uncoded differential phase shift keying (DPSK) systems which are common for voice transmission as in Bluetooth. In differentially modulated systems, the receiver usually employs a non-coherent demodulation. We propose a novel receiver architecture for non-coherent demodulation, that employs a notch filter in conjunction with a FBF of a DFE, to remove a spur without enhancing ISI. We analyze the performance of the proposed architecture for non-coherent demodulation and derive some important results.

The rest of the paper is organized as follows. Section 2 describes the proposed solution and the system model. Section 3 describes non-coherent demodulation technique and also shows how it can be extended for the coherent demodulation technique. Section 4 presents the simulation results and section 5 concludes the paper.

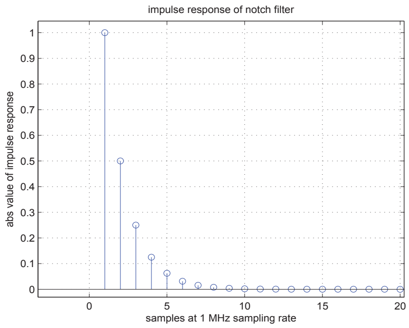

Fig. 1. Impulse response of the notch filter

2. FBF FOR NOTCH FILTER

One obvious solution to suppress the spur is to add a notch filter to the signal path in the digital baseband. A digital notch filter can be designed by placing a zero on the unit circle at an angle corresponding to the frequency of the spur. A first order IIR implementation is of the form

$$\frac{1 - z^{-1}e^{j\theta}}{1 - \alpha z^{-1}e^{j\theta}} \tag{1}$$

However, the inclusion of notch filter to suppress the spur introduces ISI. In an uncoded system, the performance can severely degrade due to the ISI. In fact the bit error rate (BER) curves can hit a floor even at very high signal to noise ratio (SNR). So for the notch filter to be a viable solution the ISI introduced by it needs to be mitigated.

Typically, most the of the systems have a linear equalizer to compensate for the multipath channel and the same equalizer can be used to reduce the ISI. However, this will just invert the impulse response of the notch filter thereby negating its effect on the spur suppression.

Instead, we exploit the fact that the notch filter in (1) has an IIR impulse response with a dominant first tap as shown in Fig. 1. A DFE can be used to remove the ISI introduced by the notch filter. In this case, the feedforward filter turns out to be a single tap filter and the FBF uses the past symbol decisions to remove the post-cursor ISI. The FBF has no impact on the spur suppression as only the sliced symbols are used. The coefficients of the FBF are just the coefficients of the impulse response and the length of the FBF can be chosen to achieve a required performance.

2.1. System Model

We consider an uncoded 8DPSK system as used in Bluetooth EDR. We also assume that the frequency and timing synchronization parameters are determined and appropriately corrected. A root-raised cosine (RRC) filter with 40% excess bandwidth is used at both transmitter and receiver and

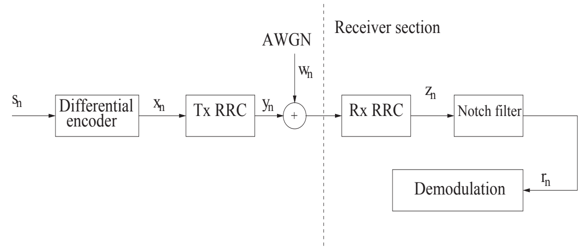

Fig. 2. System Model

an AWGN channel is assumed. The notch filter implementation as described in (1) is assumed. Fig. 2 shows the system model and the notations that are followed at the input and output of each block. Due to differential modulation, the symbol transmitted at time instant n is given by

$$x_n = x_{n-1}s_n \tag{2}$$

where x_{n-1} is the symbol transmitted at time instant $n-1$ and s_n is the information symbol corresponding to time instant n. In the following section we describe the receiver architecture for non-coherent demodulation.

3. NON-COHERENT DEMODULATION

Let the phase offset between the transmitter and receiver local oscillators be represented by θ. Furthermore, assuming that the Tx RRC and Rx RRC are matched and the output of Rx RRC is sampled at the correct time instants, the output of Rx RRC can be written as

$$z_n = e^{j\theta}x_n + w_n \tag{3}$$

We assume that the truncated FIR response of the IIR notch filter has length L and that its impulse response is $h_i, i = 0, 1, 2 \cdots L-1$. Since $h_0 = 1$, the output of the notch filter can be written as

$$r_n = e^{j\theta}(x_n + \underbrace{\sum_{i=1}^{L-1} h_i x_{n-i}}_{ISI}) + \sum_{i=0}^{L-1} h_i w_{n-i}. \tag{4}$$

The ISI introduced by the notch filter is denoted by

$$\Sigma_{n-1} = \sum_{i=1}^{L-1} h_i x_{n-i}. \tag{5}$$

Assuming a noiseless case and using (4) and (5), we can write

$$\begin{aligned} r_n &= e^{j\theta}\left(x_n + \Sigma_{n-1}\right) \\ r_{n-1} &= e^{j\theta}(x_{n-1} + \Sigma_{n-2}) \end{aligned} \tag{6}$$

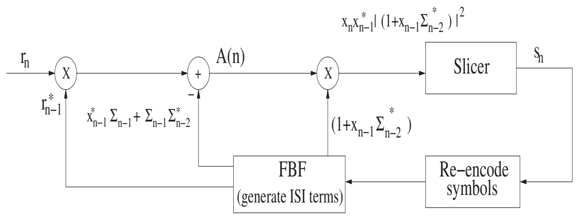

Fig. 3. Non-coherent demodulation receiver

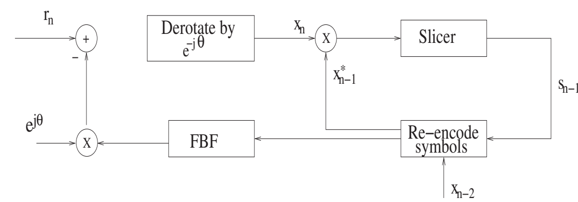

Fig. 4. Receiver structure when the phase offset is estimated

In non-coherent demodulation the phase offset θ is not estimated. Therefore, to get rid of the dependence on θ, $r_n r^*_{n-1}$ is computed and fed into the slicer. Thus,

$$r_n r^*_{n-1} = x_n x^*_{n-1} + x_n \Sigma^*_{n-2} + I(n-1) \tag{7}$$

where,

$$I(n-1) = x^*_{n-1}\Sigma_{n-1} + \Sigma_{n-1}\Sigma^*_{n-2}. \tag{8}$$

$I(n-1)$ is the ISI introduced by the previous symbols and can be canceled out by using past symbol decisions, FBF filter and (5).

In a PSK system the term $x_n\Sigma^*_{n-2}$ can be modified as $x_n\Sigma^*_{n-2}(x_{n-1}x^*_{n-1})$ as the constellation points have unit norm. Thus (7) can be rewritten as

$$r_n r^*_{n-1} = x_n x^*_{n-1}(1 + x_{n-1}\Sigma^*_{n-2}) + I(n-1) \tag{9}$$

Recalling from (2), the estimate of s_n is contained in the angle information of $x_n x^*_{n-1}$, i.e., $s_n = x_n x^*_{n-1}$. Therefore, the following steps need to be followed for ISI removal and demodulation in non-coherent demodulation case:

1. Re-encode the transmitted symbols $x_n = x_{n-1}s_n$.
2. Compute the terms $I(n-1)$ and $A(n) = r_n r^*_{n-1} - I(n-1)$.
3. Compute the term $B(n-1) = (1 + x_{n-1}\Sigma^*_{n-2})$.
4. The product $A(n)B^*(n-1)$ is then fed to the slicer.

Fig.3 shows this structure for non-coherent demodulation. In this architecture, in the absence of decision errors of past symbols we can perfectly remove the contribution of the ISI term introduced by the notch filter.

3.1. Signal "Fading" in Non-coherent demodulation

In (9), we saw that the signal term of $x_n x^*_{n-1}$ is multiplied by the term $B(n-1)$ which is in fact a random variable and hence results in the "fading" of the signal. The term $B(n-1)$ can be rewritten as

$$B(n-1) = 1 + \sum_{i=1}^{L-1} h^*_i (x_{n-1}x^*_{n-1-i}). \tag{10}$$

The constellation points, x_n, are i.i.d random variables with zero mean and unit variance therefore for reasonably large L, $B(n-1)$ can be approximated as a complex circular Gaussian random variable with unit mean and variance given by (11).

$$\sigma_b = \sum_{i=1}^{L-1} |h_i|^2. \tag{11}$$

Due to scaling by B, the signal experiences a Ricean fading which results in the loss in system performance. The performance loss increases with the norm of the FBF filter.

If the non-coherent demodulation is performed by estimating the unknown phase, the ISI cancellation can be performed at the input of the demodulator as shown in Fig. 4. The output of the slicer can be used to re-construct the transmitted symbols. The ISI term can be computed using these reconstructed symbols which can be rotated with the estimate of the phase offset. This rotated ISI term can be subtracted from (6). In this demodulation scheme, the signal term is not scaled by the "fading" term B. Therefore, even for non-coherent demodulation of DPSK systems it is better to estimate the unknown phase. If the phase is estimated then the non-coherent demodulation of Fig. 4 is equivalent to coherent demodulation.

4. SIMULATION RESULTS AND DISCUSSION

An uncoded 8DPSK system as described in Section 2.1 is considered. When the signal to spur power ratio is 10 dB, non-coherent demodulation without the notch filter shows performance degradation of 12 dB compared to the ideal performance. Now, in the proposed solution we consider two notch filters one providing 40 dB attenuation and the other 25 dB attenuation. The impulse response of the notch filter 1, for notch at 200 KHz with $\alpha = 0.5$ in (1) and sampling frequency of 1 MHz is shown Fig. 1. This provides an attenuation of 40 dB at 200 KHz.

The BER performance is simulated with and without the DFE. The FBF of the DFE has a length of 8 taps. The BER performance with notch filter is shown in Fig. 5. There is a very high BER floor with notch filter and no FBF indicating that the ISI is very high. This BER floor is removed by the FBF in both coherent and non-coherent demodulation. In fact, the coherent demodulation performance with FBF is within

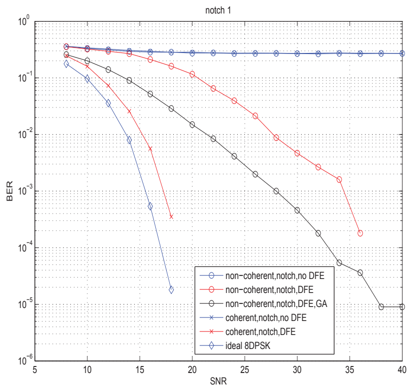

Fig. 5. BER performance for Notch filter 1

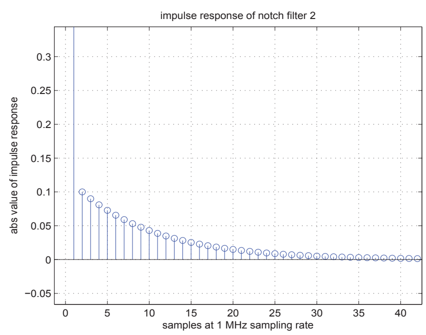

Fig. 6. Impulse response for notch filter 2

2dB from the ideal performance. However, non-coherent demodulation has large gap from the ideal performance due to error propagation by FBF and Ricean fading of the signal.

Fig. 5 also plots genie-aided (GA) non-coherent demodulation to understand the impact of error propagation of FBF. At BER of 1e-2 there is 6 dB degradation in performance because of the error propagation by FBF whereas Ricean fading of the signal causes 11 dB degradation as compared to coherent demodulation. This is because the taps of the notch filter are large and the variance of the fading component given by (11) is high.

Fig.6 plots the impulse response for notch filter 2 which is designed with $\alpha = 0.9$ and has an attenuation of 25 dB at 200 KHz. It can be seen that the impulse response is very long but the taps are not as strong as compared to that of notch filter in Fig. 1. In this case the length of FBF should be at least 20 taps to remove the ISI. Fig.7 shows the performance of notch filter 2. The degradation due to Ricean fading component is 2.5 dB when compared to coherent demodulation.

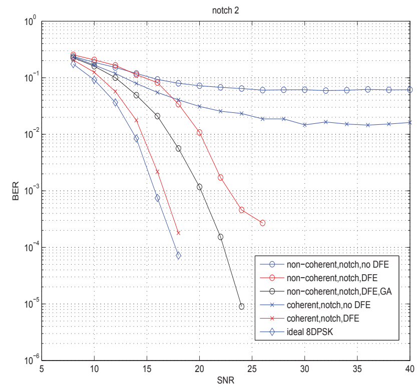

Fig. 7. BER performance for Notch filter 2

5. CONCLUSIONS

We showed that with the notch filter in the Rx chain the BER curve has a floor if the ISI introduced by the notch filter is not corrected. The non-coherent demodulation can perfectly cancel the ISI term in the absence of the decision errors of the past symbols. However, the signal is scaled by a "fading" term which can cause significant performance degradation. We also showed that for DPSK systems phase estimation in non-coherent demodulation removes the scaling by the "fading" term and provides significant performance improvement. The proposed method also has the flexibility to trade-off the attenuation of the notch filter with the length of the FBF.

6. REFERENCES

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