Effects Of 1/F Baseband Noise And Its Suppression Using Kalman Filter In OFDM System

Ravi Kumar, Anil Kumar, Arvind Kumar Jaiswal
ECE Department SHIATS-DU Allahabad India 211007

Abstract

The additive 1/f noise is a system noise generated due to miniaturization of hardware and affects the lower frequencies. Though 1/f noise does not show much effect in wide band channels because of its nature in case of lower frequencies.1/f noise becomes prominent in OFDM communication systems where narrow band channels are used. In this paper, we study the effects of 1/f noise on the OFDM systems and implement the algorithms for estimation and suppression of the noise using Kalman filter. Suppression of the noise is achieved by subtracting the estimated noise from the received noise.

1. Introduction

The growing demand for smarter, smaller, low power consuming devices with considerably good quality of service has given rise to development of more efficient devices and many techniques to improve these devices. All these devices are exemplified by various resources such as size, power, spectrum and other consumer needs. These characteristics are the reason for the constant development in smaller devices whose size is reducing considerably depending on consumer needs and also not compromising efficiency and quality of service. The goal is to improve quality of service expected by consumers by minimizing additional 1/f noise introduced in the system due to miniaturization of hardware. Miniaturization of hardware to increase speed and packing density has led to considerable reduction of size of transistors whose metal oxide gate has become even smaller; this led to introduction of an additional noise called flicker noise pink noise or 1/f baseband noise. 1/f noise is common in baseband analog front ends (AFE) utilizing direct-conversion RF, which are commonly used in orthogonal frequency division multiplexing (OFDM) transceivers. For a wide-band system introduction of 1/f noise around the DC is not an issue as it will only take up a small portion, but in transmission scheme such as OFDMA an user is allocated with a small portion of DC and having 1/f noise effect it becomes an issue. Thus, it is very essential to study the effect of 1/f noise on overall system. I use the noise model in [10] and implement it using Kalman filter to estimate the 1/f noise and then suppress the noise by subtracting it from the received signal. Initial work on orthogonal frequency division multiplexing (OFDM) was done in 60s and 70s. OFDM is a method of encoding data into different carriers on different frequencies [1]. As the name suggests OFDM depends on orthogonal principle, it uses subcarriers that are orthogonal to each other. The use of orthogonal subcarriers avoid crosstalk between co-channels and also eliminate the need for inter carrier guard bands. This simplifies the design of both transmitter and receiver. OFDM is a digital multicarrier transmission which uses a large number of closely spaced orthogonal subcarriers and is suited for frequency selective channels and high data rates. OFDM transmission transforms frequency selective wide-band channels into a group of non-selective narrow band channels, which make it more useful against large delay spreads [2].

In this paper we investigate the effects of 1/f baseband noise on a small frequency allocation for an LTE UE. We further utilize the 1/f noise model in [10] to estimate the 1/f noise. We show that suppression of the 1/f noise by subtracting the estimated 1/f noise from the received signal, results in a significant processing gain. The estimation of the 1/f noise is done by the well-known Kalman filter [5], which computes a new estimate for every received sample. This type of processing is appropriate for real-time systems such as an LTE UE transceiver. The UE transceiver will be most vulnerable to the 1/f baseband noise while receiving a very weak signal while operating in sensitivity, which is defined as the minimum signal received from the antenna connector[7].The reception at sensitivity is a very important parameter in a cellular system, since it determines the transceiver's capability of operating at the cell edge. In section 2 we define the system model. In section 3 we present a scheme for estimating the 1/f baseband noise using a Kalman filter. In section 4, an applicative example is given for an LTE UE transceiver. We explore the damages of the 1/f baseband noise on small frequency allocations around the DC. We suppress the 1/f noise by subtracting the 1/f noise estimation from the received signal. The suppression of the 1/f noise results in considerable processing gain.

2. System Model

In order to estimate 1/f noise we follow the noise model given in [10]. This model is developed using N+1 first-order differential equations, where N is a model parameter. The 1/f noise model is given by

$$\begin{aligned}
\dot{y}_{2N}(t) &= y_{2N}(t) - y_{2N}(0) + \\
&\quad 2\left[\nu(t) - \phi(t) - 2\sum_{k=1}^{N} y_{2k}(t)\right] \\
\dot{y}_{2N-2}(t) &= y_{2N-2}(t) - y_{2N-2}(0) - 4y_{2N}(t) + \\
&\quad 4\left[\nu(t) - \phi(t) - 2\sum_{k=1}^{N-1} y_{2k}(t)\right] \\
\dot{y}_{2N-4}(t) &= y_{2N-4}(t) - y_{2N-4}(0) - 4y_{2N}(t) - \\
&\quad 8y_{2N-2}(t) + 6\left[\nu(t) - \phi(t) - 2\sum_{k=1}^{N-2} y_{2k}(t)\right] \\
&\vdots \\
\dot{y}_{2}(t) &= y_{2}(t) - y_{2}(0) - 4\sum_{m=1}^{N-1} m y_{2(N-m+1)}(t) + \\
&\quad 2N\left[\nu(t) - \phi_n(t) - 2y_2(t)\right] \\
\dot{\phi}(t) &= -(2N+1)\phi(t) - \phi(0) - \\
&\quad 4\sum_{m=1}^{N} m y_{2(N-m+1)}(t) + 2(N+1)\nu(t),
\end{aligned} \tag{1}$$

where v(t) is a white Gaussian noise and Φ(t) is the approximated 1/f Gaussian process. Therefore, Nth approximation to the 1/f noise process is an output of a Markovian system of N+1 linear stochastic differential equations [11] [12]. The above equations can also be written as

$$\dot{x}(t) = Ax(t) + Bv(t) \tag{2}$$

Where the matrices A and B are given by

$$A = \begin{bmatrix} -3 & -4 & -4 & . & . & . & -4 & -2 \\ -4 & -7 & -8 & . & . & . & -8 & -4 \\ -4 & -8 & -11 & . & . & . & -12 & -6 \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ . & . & . & . & . & . & . & . \\ -4 & -8 & -12 & . & . & . & -4N-1 & -2N \\ -4 & -8 & -12 & . & . & . & -4N & -2N-1 \end{bmatrix} \tag{3}$$

And

$$B = \begin{bmatrix} 2 \\ 4 \\ . \\ . \\ . \\ 2N \\ 2(N+1) \end{bmatrix} \tag{4}$$

Respectively and the state vector x(t) is defined as

$$x(t) = \begin{bmatrix} y_{2N}(t) \\ y_{2N-2}(t) \\ . \\ . \\ . \\ y_2(t) \\ \phi(t) \end{bmatrix} \tag{5}$$

Equation (2) describes the model for 1/f noise for a continuous time where as a model for discrete time has to be obtained. In [13] the author derived a discrete time model from a continuous one. It is defined as follows, let

$$\boldsymbol{C} = \begin{bmatrix} -\boldsymbol{F} & \boldsymbol{QGG}^T \\ \boldsymbol{0} & \boldsymbol{F}^T \end{bmatrix} \tag{6}$$

where Q is used to control 1/f noise intensity. Let

$$e^{C_{\Delta_t}} = \begin{bmatrix} A_2 & B_2 \\ 0 & A_3 \end{bmatrix} \tag{7}$$

where Δt is time sample between two samples of discrete process. Now using equations (3) and (7) we can define

$$Q_d = A_3^T B_2 \quad (8)$$

$$\Phi = e^{A^{\Delta} t} \quad (9)$$

From the above two equations the discrete model is given by

$$\xi_{k+1} = \Phi \xi_k + w_k \quad (10)$$

where wk is an independent Gaussian vector process with covariance matrix Qd. ξ_k is the desired 1/f sampled process [11]. The 1/f noise spectral density can be given by

$$S\phi\phi(f) = Q/2\pi|f| \quad (11)$$

The complex envelop of an OFDM signal can be expressed as

$$s(t) = (h(t) \otimes \Sigma\, a_m e^{j^2 \pi mT\, t}) \quad (12)$$

where data am modulated the sinusoid at frequency m/T during symbol time T and h(t) denotes the channel impulse response [11]. The received complex signal r_k at the transceiver's baseband is given by the equation

$$r_k = s_k + v_k + \phi_{I,k} + j\phi_{Q,k} \quad (13)$$

where v_k is a circular complex additive Gaussian thermal noise process and both $\phi_{I,k}$, $j\phi_{Q,k}$ have spectral density. Thermal noise Variance v_k is defined such that it has N_0 variance for every subcarrier in the frequency domain

3.Noise Estimation Scheme

Using the discrete mode l in equation (10) Kalman filter is applied to estimate the noise processes $\phi_{I,k}$ and $\phi_{Q,k}$. The observation mode l is given by equation (12). The estimation of $\phi_{I,k}$ is done on real part of r_k whereas the estimation of $\phi_{Q,k}$ is done on the imaginary part of the received signal. The estimation equation that shall be used for recursive computation using Kalman filter is given by [11]

$$\acute{\varnothing}_{k/k} = G\xi_{k|k}$$

where G is given by

$$G^T = \begin{bmatrix} 0 \\ 0 \\ . \\ . \\ 0 \\ 1 \end{bmatrix} \quad (14)$$

The first step is the prediction step

$$\xi_{k|k-1} = A\xi_{k-1|k-1} \quad (15)$$

$$P_{k|k-1} = AP_{k-1|k-1}A^T + Q_d \quad (16)$$

where a priori predicted estimate state is given by equation (15) and estimate covariance is given by equation (16). The update step is given by following equations [11]

$$\bar{r}_k = \tilde{r}_k - G\xi_{k|k-1} \quad (17)$$

$$S_k = GP_{k|k-1}A^T + V \quad (18)$$

$$Kk = P_{k|k-1}G^T S_k^{-1}$$

$$\xi_{k|k} = \xi_{k|k-1} + K_k\bar{r}_k \quad (19)$$

$$P_{k|k} = (I - K_k G)P_{k|k-1} \quad (20)$$

where the observation $\tilde{r}_k$ can be either real or imaginary. V is the variance of s_k+v_k . Sk is the innovation covariance, K_k is the optimal Kalman gain. Equations (19) and (20) give the updates state estimate and covariance [11]. The initial conditions are taken as

$$\xi_{0|0} = 0,\ P_{0|0} = 0 \quad (21)$$

The variance V can be estimated either by estimating the power of received samples at the output high pass filter with a low frequency cutoff at 1/f noise corner frequency or by subtracting the estimated 1/f noise power from the total of the received samples [14]. In [11] the author has worked on elimination of 1/f baseband noise in an OFDM system using an environment closer to real time environment and also taking into consideration relative motion between transmitter and receiver. In present paper, we have simulated similar conditions for a transmission using Raleigh fading channel.

4. Simulation Results

The steps followed in this paper to estimate and suppress 1/f noise are:

(a) Prepare additive 1/f baseband noise model where N=150 in the simulation and the estimated of the 1/f noise by Kalman filter model order of N=5 .

b) Estimate the 1/f noise in the received signal.

c) Subtract the estimated noise from the received signal.

d) Calculate errors with suppression and without suppression of baseband noise and check for better performance of the system. The OFDM system was simulated using one transmitter and receiver antenna and both fading and non-fading channels. The additive 1/f baseband noise is generated using the equation (10) with model order of N=150. 1/f baseband noise can also be generated using an exact model given in [13][11]. This is given by equation.

$$\phi_n = \Sigma^{n}_{k=1} -a_k \phi_{n-k} + u_n \qquad (22)$$

where coefficient a_k is given by

$$a_0 = 1,\ a_k = (k-1-1/2)\ a_{k-1}/a_k \qquad (23)$$

The runtime for the exact model is longer than the approximated model, since in exact model generation of each new sample involves all the previous samples. This dependence helps binary better estimation of characteristics of 1/f noise. The SNR is defined as

$$SNR = E_s/N_0 \qquad (24)$$

where Es is the subcarrier means energy and N0 is the white thermal baseband noise energy for single subcarrier [11]. The following figure gives curves of block error rate (BLER) where 1/f baseband noise is not present, two curves of BLER in the presence of 1/f baseband noise one generated using equation (10) and other using equation (22) and the curve after suppression of 1/f baseband noise.

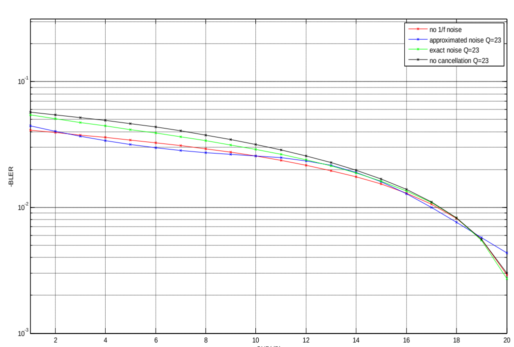

Figure 4.1 Simulation depicts relation between BLER and SNR the green curves depict the estimation done using exact model, blue curves depict estimation done using approximated model and the black curves depict system with no 1/f noise cancellation. These were done using Q as 23dB.

To get a better understanding of estimation process, the real part of received signal, the real part of 1/f baseband noise and the estimated part of 1/f baseband noise are presented in the next simulation. Considering $s_k + v_k$ to be the desired signal, normalized least mean square error (NMSE) [11] before suppression is given by

$$NMSE = 10\ log_{10} \frac{\Sigma|\phi_{I,k} + j\phi_{Q,k}|^2}{\Sigma|s_k + v_k|^2} \qquad (25)$$

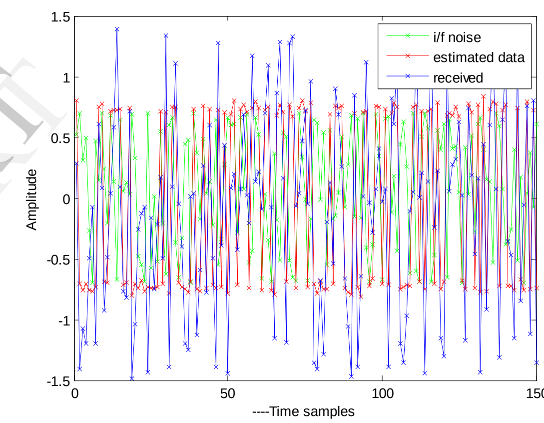

Figure 4.2 Simulation depicting the time domain phase noise estimation: the blue signal is the received signal, the green signal is the 1/f noise, and the red signal is the estimation of 1/f noise from the received signal.

The gains resulting in suppression of 1/f baseband noise can be represented by plotting remaining 1/f baseband noise and the processing gain. This simulation is shown in the following Plot

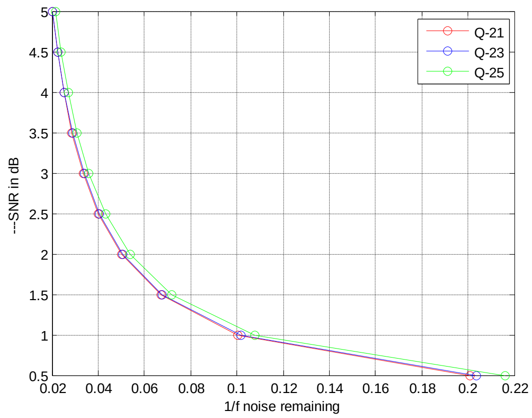

Figure 4.3 Simulation depicting the processing gain vs. the remaining 1/f baseband noise levels after suppression

The processing gain is higher for higher Q, this is because the total level of suppressed noise is higher for higher Q even when the normalized remaining noise is the same. All the above simulations were performed taking N =150. Now to estimate the proper order to get good estimation simulation for different N is shown below.Figure 4.4

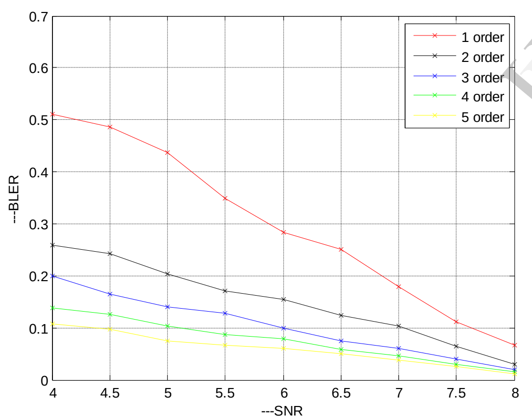

Figure 4.4 Simulation depicting BLER vs. SNR for different approximation orders. The noise level was set at Q= 19dB

It is show that an approximation of order N=5 is enough to achieve acceptable results. As the 1/f noise is mainly concentrated in the corner frequencies the estimation can be performed after the received signal is passed through a low pass filter. This would save computation time.

It can seen that in the figure 4.5 the BLER is given as fuction of Q for constant SNR .It can clearly seen that 1/f baseband noise suppression is useful for large allocation.

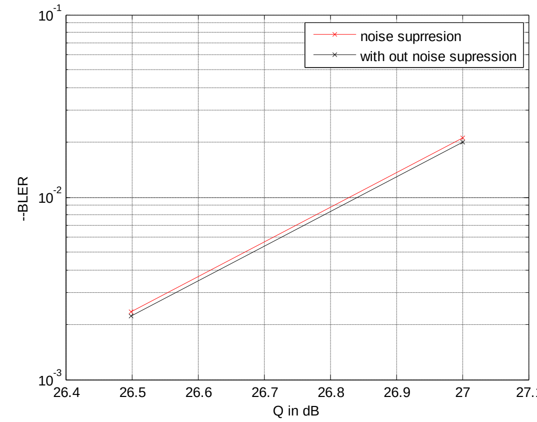

Figure 4.5 Simulation depecting BLER vs Q.Red curve denote the BLER when suppression of1/f noise is not applied and black line denote the BLER when suppression of 1/f noise is applied.

5. Conclusion

The effects of 1/f noise in an OFDM system were investigated and the performance of system after the suppression of 1/f noise was shown through a series of simulations which showed increase in processing gain of the system which can be used in design and implementation of systems. In this paper, a 1/f noise suppression algorithm was implemented using Kalman filter over an OFDM system using a non-fading awgn channel. Thus the Kalman filter is used in estimation of 1/f baseband noise during a communication and in improving the quality of communication by suppressing the noise using the estimate given by the filter.

6. References

[1] Matiae. D, "OFDM as a possible modulation technique for multimedia applications in the range of mm waves", Introduction to OFDM, II edition, 1998.

[2] M. Debbah, "Short introduction to OFDM", White Paper, Mobile Communications Group, Institute Eurecom, February 2004.

[3] Rachel Kleinbauer, "Kalman Filtering Implementation with Matlab", study report, University Stuttgart, Helsinki, November 2004.

[4] Greg Welch and Gary Bishop, "An Introduction to the Kalman Filter", Technical Report, University of North Carolina at Chapel Hill Chapel Hill, NC, USA,1995.

[5] D. Simon, "Kalman Filtering, Embedded Systems Programming", vol. 14, no. 6, pp. 72-79, June 2001.

[6] Chew, K.W. Yeo, K.S. Chu, S.-F.;"Impact of technology scaling on the 1/f noise of thin and thick gate oxide deep submicron NMOS transistors, Circuits, Devices and Systems" Proceedings of the IEEE, vol.151, no.5, pp. 415- 421, 15 Oct. 2004

[7] Won Namgoong, Meng T.H., "Direct-conversion RF receiver design, Communications", Proceedings of the IEEE, vol.49, no.3, pp.518-529, Mar 2001

[8] S. Landis, Z. Schuss, and B. Z. Bobrovsky, "The exit problem in a nonlinear system driven by 1/f noise: the delay locked loop", SIAM J. Appl. Math., vol. 66, pp. 1188-1208, Apr. 2006

[9] Landis S, Bobrovsky B. Z., "1/f Baseband Noise Suppression in OFDM Systems, Communications", Proceedings of the IEEE, vol.59, no.4, pp.942-947, April 2011

[10] Z. Schuss, "Theory and Applications of Stochastic Processes: An Analytical Approach". Springer, 2010

[11] Kasdin N.J., "Discrete simulation of colored noise and stochastic processes and 1/fα power law noise generation", Proceedings of the IEEE, vol.83, no.5, pp.802-827, May 1995

[12] Georgiadis A., "AC-coupling and 1/f noise effects on baseband OFDM signals", Communications Proceedings of the IEEE, vol.54, no.10, pp.1806-1814, Oct. 2006.

[13] http://en.wikipedia.org/wiki/quadrature, amplitude modulation

[14] http://en.wikipedia.org/wiki/Phase-shift_keying