Frequency Tracking Performance Using a Hyperbolic Digital-Phase Locked Loop for Ka-Band Communication in Rain Fading Channels

Kandeepan Sithamparanathan and Radoslaw Piesiewicz

Create-Net International Research Centre,
via alla Cascata 56/D, Trento, 38100, Italy
{Kandee,Radoslaw.Piesiewicz}@create-net.org

Abstract. In this paper we study and present some results on the performances of frequency tracking for Ka-band satellite communications in rain fading channels. The carrier frequency is tracked using a 2nd order hyperbolic phase detector based digital-phase locked loop (D-PLL). The hyperbolic D-PLL has the capability of extending the tracking range compared to the other D-PLL and hence can be designed such that to achieve low phase jitter performance for improved carrier tracking. We present the design and analysis of the D-PLL and show some simulation results on the frequency tracking performance for Ka-band rain fading channel. The results are compared with the non-fading noise only case and comparative analyses are made.

Keywords: Frequency tracking, digital-phase locked loops, hyperbolic phase detector, Ka-band frequency tracking.

1 Introduction

Higher frequency transmission for satellite communication is of great interest in the current era to have high speed video transmission and broadband internet access. The currently available Ka-frequency-band, with 30GHz uplink and 20GHz downlink for satellite communications, is one of the frequency bands that could deliver such high speed communication links to and from the satellites by exploiting the wider bandwidth available at such frequencies.

Frequency synchronization is quite crucial for high speed communication especially at higher frequencies such as for the Ka-band. Excess frequency or phase jitter in the receiver may lead up to losing the link, especially when the received signal power is quite low, due to increasing bit errors cause due to synchronization errors. Hence precise frequency synchronization is considered to be very crucial especially at higher frequency bands. In general, a standard level of jitter can be accepted in order to achieve a certain value of probability of bite error at the receiver, however when there is fading, the signal level fluctuation (signal power fluctuation) may lead to excess jitter in the estimated frequency leading towards unacceptable levels of bit error rates. In this paper we study the performance of frequency tracking using digital-phase locked loop (D-PLL) under rain fading conditions for the Ka-band

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channel. There exist several feed forward and feedback frequency synchronization techniques [10] however D-PLL is considered to be computationally efficient which draws our interest.

Digital-phase locked loops are used to track signal frequencies in communication systems [3,5] for local frequency synchronization. Traditionally the phase locked loops have a trade-off between the acquisition performance and the tracking performance based on the loop parameter known as the closed loop bandwidth B_L. Having a higher value for the loop bandwidth enables to acquire wider range of frequencies but at the same time increases the phase noise during tracking after acquiring the frequency. The increase in phase noise (hence the increase in the instantaneous frequency jitter) will degrade the probability of bit error at the receiver. The hyperbolic phase detector based digital phase locked loop [4] due to its nonlinear characteristics enhances the tracking range of the frequency, which then allows us to reduce the value of B_L (note that B_L is defined only with respect to a linear loop [3,5]) for the corresponding phase locked loop and hence reducing the phase jitter during the tracking mode compared to the standard digital phase locked loop.

In this paper we study the performance of such a hyperbolic digital phase locked loop when it is used to track carrier frequencies for Ka-band satellite communications under rainy fading channel conditions. The Hyperbolic D-PLL is used due to its extended tracking capabilities instead of the standard D-PLL [4]. We consider the baseband system model in our analysis and track the frequency error present at the baseband signal. In [4] the loop model for the hyperbolic digital phase locked loop is presented and the performance analysis of the loop is also studied for the additive Gaussian noise only case. In this paper we consider a similar model for the phase locked loop and extend the analysis for a Ka-band fading channel with additive noise.

The rest of the paper is composed with the following sections. In Section-2 and Section-3 we provide the communications system model at Ka-band and the loop model for the hyperbolic digital phase locked loop, respectively. In Section-4 we present some theoretical analysis on the phase locked loop for non-fading conditions, and in Section-5 we present some simulation results on the performance of the phase locked loop and compare the results with the non-fading theoretical case. Finally, we provide some concluding remarks.

2 Communication System and Ka-Band Channel Models

Figure-1 shows the communication system model that is considered in our work. At the transmitter on the satellite, the raw digital data is mapped into symbols and passed trough the pulse shaping filter to band limit the signal to reduce inter symbol interference. The pulse shaping filter used here is the square root raised cosine filter with a roll factor α defining the bandwidth of the transmitted signal. The filtered signal is then passed through a QPSK modulator before transmitting it through a parabolic dish antenna thorough the Ka-band communication channel. The Ka-band communication channel is modeled as a rainy fading channel as described in [6]. The received signal is then demodulated and processed for signal frequency, timing and phase synchronization in order to detect and decode the received symbols.

In our model we assume perfect timing synchronization in order to make the analysis easier, and furthermore we do not consider any channel equalizer specifically to analyze the performance of frequency tracking under rain fading conditions. The received baseband signal in its complex envelope form is given by,

$$r = h(t)s(t) + n(t) \tag{1}$$

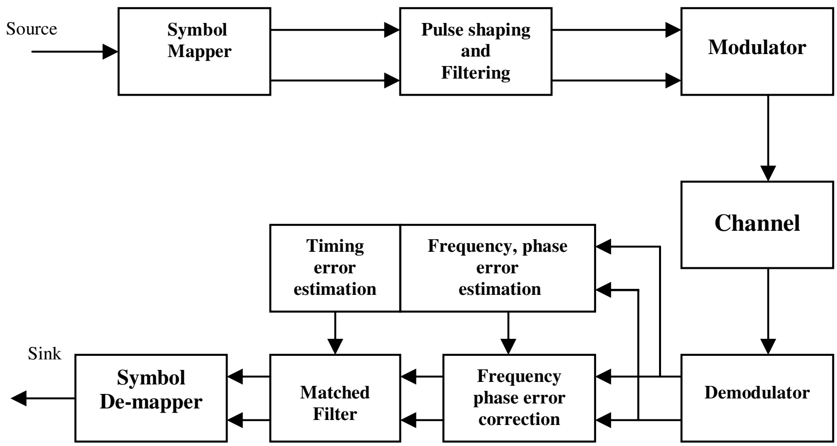

Fig. 1. The Communication System model considered to analyse the performance of the Hyperbolic Digital- Phase Locked Loop

where, h(t) is the rain fading channel at Ka-band in its complex envelope form given by,

$$h(t) = h\_I(t)+jh\_Q(t) \tag{2}$$

where h_I and h_Q follow the statistical distribution as described in [6]. We follow the method described in [6] to model the rain fading channel, and the readers are recommended to read [6] for a detailed explanation of the channel model. The complex envelope s(t) of the received signal at the baseband, with a bandwidth of Bw and a frequency error of Δf which is to be tracked, is given by,

$$s(t) = \Sigma\, c\_m{*}g(t - mT)\exp(-j2\pi\Delta ft+j\beta) \tag{3}$$

where, c_m is the m^{th} data symbol given by, c_m = a_m + jb_m, with a_m and b_m are elements of the set {-1,1}, g(t) is the square root raised cosine pulse, and T is the symbol duration. The additive noise n(t) is a zero mean band limited complex Gaussian process given by,

$$n(t) = n\_I(t) + jn\_Q(t) \tag{4}$$

where, n_I(t) and n_Q(t) are the inphase and the quadrature components each with noise power of σ^2 each.

3 The Hyperbolic Digital Phase Locked Loop

The loop model considered is given in Figure-1. It consists of an error detector or a phase detector (PD), a loop filter and a numerically controlled oscillator (NCO). The NCO is equivalent to the voltage controlled oscillator (VCO) of its analog counterpart.

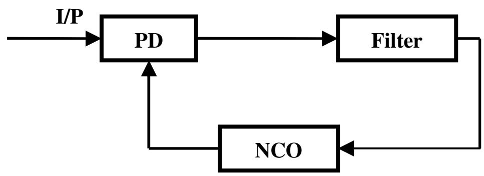

Fig. 2. Digital phase locked loop model

The PD is a four-quadrant arctan PD that maps the input arguments to its corresponding four quadrant phase plane, which is followed by a hyperbolic function. The block diagram of the PD model is shown in Figure-3. The output signal **x** from the NCO is given by,

$$x[n] = \exp\{-j\,\theta[n]\} \tag{5}$$

The multiplier in Figure-3 is a complex multiplier. The output of the multiplier is fed into the arctan function, and the resulting phase is passed through a hyperbolic function g(.),

$$\varphi_e = g(\varepsilon) = \sinh(\varepsilon) \tag{6}$$

where, in (6), ε is given by,

$$\varepsilon = \arctan\{u,v\} \tag{7}$$

where, u and v are the real and imaginary components of the output of the complex multiplier as shown in Figure-3.

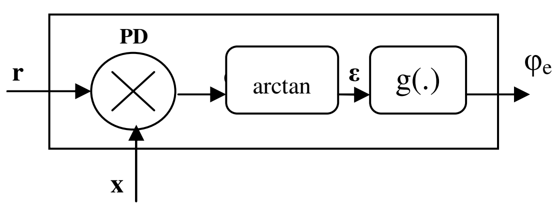

Fig. 3. The Hyperbolic phase detector model

The mathematical model of the loop without the nonlinear hyperbolic g(.) function is given by its closed loop transfer function H(z),

$$H(z) = \frac{D(z)V(z)}{1 + D(z)V(z)} \tag{8}$$

where, D(z) and V(z) are the discrete transfer functions of the loop filter and the NCO respectively, which are given by,

$$D(z) = \frac{az}{[z - (1 - a)]} \quad \text{and} \quad V(z) = \frac{k}{z - 1} \tag{9}$$

where, a is the filter co-efficient and k is the NCO parameter that controls the loop.

3.1 Lock-In Range

The lock in range of the loop is defined by the maximum frequency deviation Δf that can be locked-in by the loop. From [4] we see that the lock-in range for the D-PLL is given kf_s/2, and for the hyperbolic loop it is given by sinh(π)kf_s/(2π), where f_s is the sampling frequency of the discrete system. From these two equations we clearly see that the hyperbolic loop can lock-in wider range of frequencies.

4 Theoretical Loop Analysis

We arte interested in the phase noise distribution of the loop for the hyperbolic phase detector based digital phase locked loop. For the additive noise only case the open loop phase noise distribution is given by,

$$f_{\varphi_e}(\varphi_e) = \cosh(\varphi_e)\, P_\lambda(\lambda) \tag{10}$$

where, $\lambda = \sinh^{-1}(\varphi_e)$ and $P_\lambda(\lambda)$ is given by,

$$P_\lambda(\lambda) = \begin{cases} \exp(-\rho/2)\left[\frac{1}{2\pi} - \exp(\frac{\Gamma_1}{2})(\frac{\Gamma_1}{2\pi})^{1/2} Q(\sqrt{\Gamma_1})\right] & for\ \pi/2 < \lambda \le \pi \\ \exp(-\rho/2)\left[\frac{1}{2\pi} + \exp(\frac{\Gamma}{2})(\frac{\Gamma}{2\pi})^{1/2} (1 - Q(\sqrt{\Gamma}))\right] & for -\pi/2 \le \lambda \le \pi/2 \\ \exp(-\rho/2)\left[\frac{1}{2\pi} - \exp(\frac{\Gamma_2}{2})(\frac{\Gamma_2}{2\pi})^{1/2} Q(\sqrt{\Gamma_2})\right] & for -\pi < \lambda \le -\pi/2 \end{cases} \tag{11}$$

where, ρ is the signal to noise ratio and,

$$\Gamma = \frac{\rho}{1+\alpha^2},\ \Gamma_1 = \frac{[\tan(\pi+\alpha)\mu_1 + \mu_2]^2}{\sigma^2[1+\tan^2(\pi+\alpha)]},\ \Gamma_2 = \frac{[\tan(-\pi+\alpha)\mu_1 + \mu_2]^2}{\sigma^2[1+\tan^2(-\pi+\alpha)]} \tag{12}$$

and,

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^{\infty} \exp(-u^2/2).du \ , \ \mu_1 = \sin(\varphi_{ss}), \ \mu_2 = \cos(\varphi_{ss}) \tag{13}$$

where, φ_{ss} is the steady state value of the phase error process φ_e.

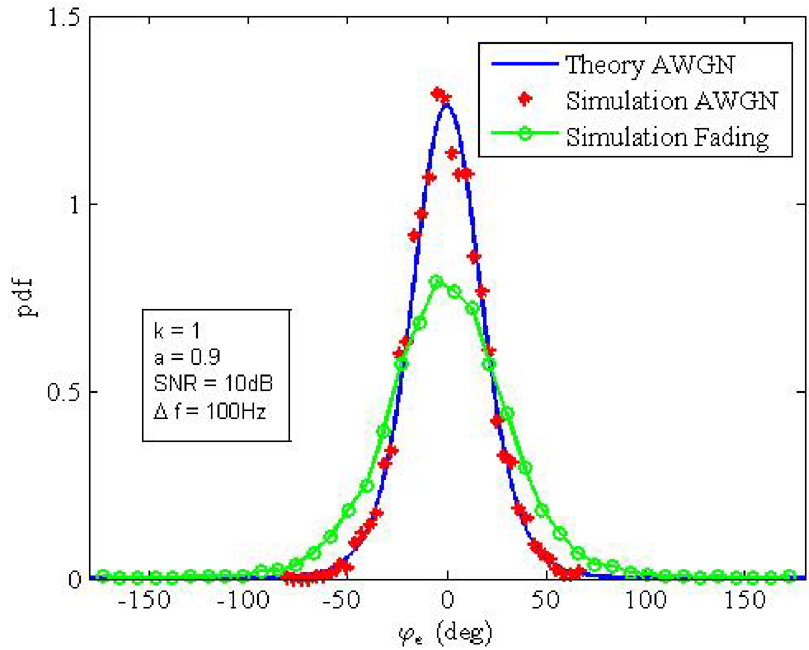

Fig. 4. the open loop phase noise distribution comparison for the hyperbolic digital phase locked loop, for AWGN noise only case and with the rain fading case

In our study we compare the statistical distribution of the phase noise in the loop for the additive noise only case and when the loop is operating in the rain fading channel environment.

The comparison study will show the differences between the two and the corresponding performance degradation under rainy fading conditions. Figure 4 depicts the phase noise distributions for the theoretical (AWGN only), simulation with AWGN only, and the simulation with rain fading environment. From the figure we clearly observe the degradation in the performance of the carrier tracking loop for the fading case, as expected. Furthermore, characterizing the noise distribution under fading conditions is also of high interest to us in order to predict the performance degradation associated with the fading conditions.

5 Phase Noise Analysis

The phase jitter analysis for the Ka-band rain fading channel is also of great interest to us in order to estimate the average bit error rate measure due to synchronization errors. Figure-5 depicts the instantaneous phase error with time for the AWGN noise only case and the rain fading case. In the figure we see some several instantaneous jumps (impulsive like noise) in the phase error process for the rain fading case due to strong/deep fading situations in the channel. On the other hand, we also observe that the AWGM noise only case has a prescribed jitter value associated with the phase error with time.

Figure-6 depicts the phase jitter performance of the hyperbolic digital phase locked loop for the AWGN only case as well as the rain fading case. The deviation in the phase jitter performance is quite significant as we observe from the figure for the values of k=0.4, a=0.9 and a frequency error at the baseband of Δf = 50Hz. Such degradation may lead to excessive bit error rate degradation and eventually leading towards an instantaneous loss of the communication link.

We also study the performance improvement in the phase jitter for the hyperbolic loop and compare it with the standard digital phase locked loop. Figure-7 shows the phase jitter performance for both the loops for a given lock in range of 2500Hz. For the given lock-in range, we require k=1 for the D-PLL and k=0.275 for the hyperbolic loop. However for the results shown in Figure-7 we choose k=0.5 for the hyperbolic loop. From the figure we clearly see the performance improvement in the phase jitter for the hyperbolic loop for a given lock-in range requirement.

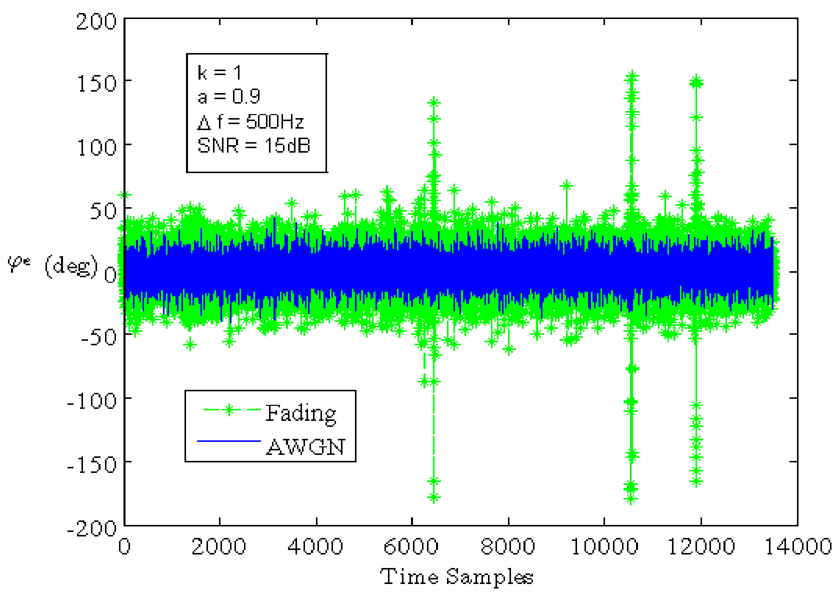

Fig. 5. Instantaneous phase error process of the hyperbolic digital phase locked loop, for AWGN only case and together with the rain fading case

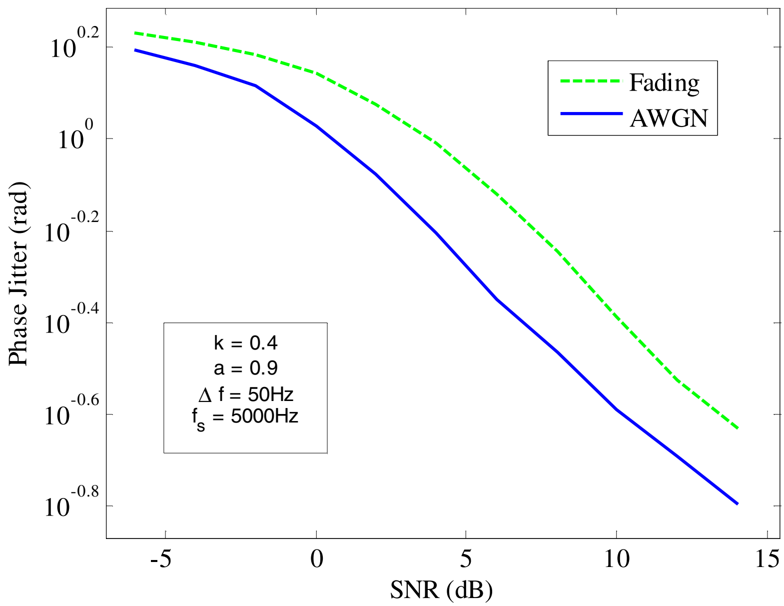

Fig. 6. Phase Jitter performance of the hyperbolic digital phase locked loop for the AWGN only case and the rain fading case

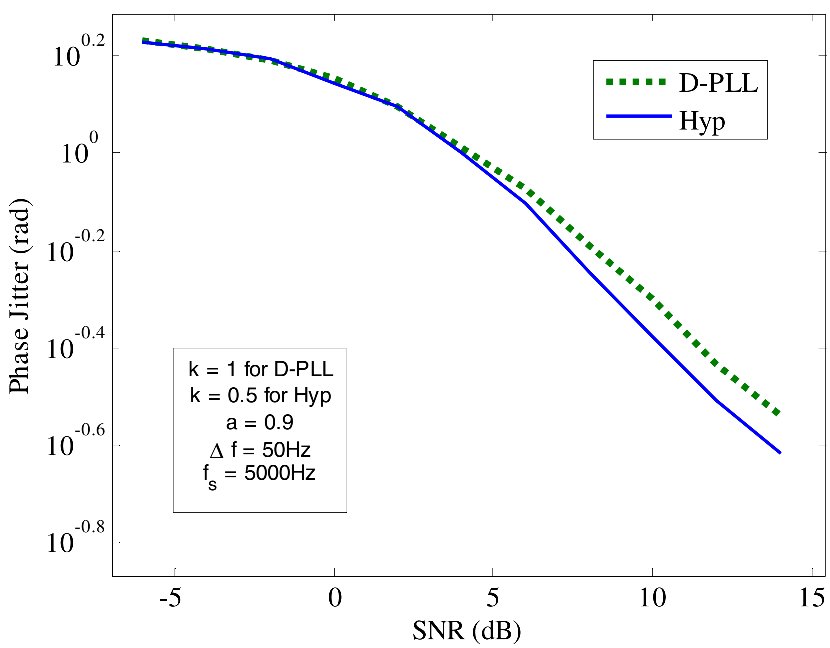

Fig. 7. Phase Jitter performance of the digital phase locked loop and the hyperbolic digital phase locked loop for the rain fading case: For a given pull-in range of 2500Hz

6 Conclusion

In this paper we studied the performance of a hyperbolic digital phase locked loop for frequency tracking for a Ka-band rain fading channel. In general conditions we observe severe performance degradation in the phase jitter performance of the phase locked loop when operating in a rain fading condition as oppose to an AWGN only channel. The hyperbolic loop, by utilizing its extended tracking (lock-in range) capability, can attain low phase jitter for frequency tracking compared to the standard digital phase locked loop.

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