Effects of Simulated Ionospheric Scintillation on a π⁄3-BPSK Demodulator to Operate on UHF Satellite Communications

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Abstract - *This article presents estimates of the performance of a π⁄3-BPSK demodulator when affected by ionospheric scintillation. This demodulator is a subsystem of a regenerative transponder to be part of new Brazilian nanosatellites, aiming to modernize the Brazilian Environmental Data Collection System (SBCDA). In previous work, the project of the demodulator was detailed for AWGN channel. In this work, the amplitude and phase fluctuations similar to those caused by ionospheric scintillation are discussed. The work shows also the block diagram of the computational system for simulations of the space communication links taking into account the discrete-time model for the π⁄3-BPSK signal and respective effects from scintillation and AWGN at the demodulator. The simulations provided estimates of the performance in terms of carrier acquisition time and bit errors rate obtained at different intensities of scintillation. In previous work, the measures showed that for AWGN channel the π⁄3-BPSK architecture satisfies the specifications of the system for both synchronization and bit error rate. However, this work shows that when affected by ionospheric scintillation the performance of the demodulator can degrade noticeably.*

Key Words: Transionospheric channel, scintillation, performance of π/3-BPSK demodulator, regenerative transponder, nanosatellites, CDTs, SBCDA, space links, symbol synchronism, carrier recover, UHF-band, amplitude and phase fluctuations.

1. INTRODUCTION

The Brazilian Environmental Data Collection System (SBCDA) using satellite is composed by the earthbound hundreds of Data Collection Terminals - DCTs operating in the UHF band (401 MHz) plus the satellites SCD1 (NORAD ID 22409) and SCD2 (NORAD ID 25504). These satellites, having non-regenerative transponders, receive the signals from the DCTs individually in the UHF band using π/3-BPSK modulation and retransmit using PM (Phase Modulation) the data from many DCTs in S band [1-3]. The π/3-BPSK is a variant of BPSK modulation with modulation index π/3 in which the carrier is not suppressed [2-4], see the spectrum on Figure 4.17 in [4].

Apart from the DCT satellites, the system also includes satellite CBERS (NORAD ID: 40336) which, in the data collection mission, receives data from DCTs in the UHF band and retransmits in S band [1, 2]. After the data arrive at the earthbound stations of INPE, the data are formatted and sent to the distribution center Coordenação Espacial do Nordeste-COENE, where the information becomes available to the end users [2, 3].

To increase and modernize the SBCDA, INPE is developing new regenerative transponders to be put in nanosatellites [3]. Differently from non-regenerative transponders these new transponders do on the satellite the following processing: a) demodulation π/3-BPSK of the signals received from the many DCTs during the sweep of the satellite; b) processing CRC of the received packets to recover the valid data from all DCTs; c) discarding the invalid data; d) new packaging of all valid received data in a single frame; e) transmission of this frame to the earthbound receiver as presented in [3].

However, due to the specificities of the dynamics of the ionosphere over the Magnetic Equator [5-7] it is recommended that the development of new orbital receivers or transponders, especially when operating over Brazil using frequencies bellow C-band, take into account estimation of the performance in links with ionospheric scintillation [5-10]. Therefore, this work aims to show estimates of the effects of scintillation on the performance of π/3-BPSK demodulator [3] as subsystem of a new regenerative transponder to be onboard the satellites of SBCDA.

In the version of the π/3-BPSK demodulator as shown in [3] the results of the computational simulations taking into account only the AWGN channel demonstrated that the solutions used for carrier recovery and symbol synchronism allow synchronization of the system in shorter time than that specified for a new transponder. Besides there is little impact on the E_b/N_0 ratio (see Figures 6 and 7 in [3]). However, the present work shows that when the effects of ionospheric scintillation are taken into account, one can observe noticeable degradation of the system as presented in section III.

Apart from presenting new performance results of error bit rate, the tests in this work also show the transitory effects while tracking the carrier during specific scintillation situations. Due to the fluctuations in amplitude and phase, it can be observed that, differently than links with only AWGN channel as shown in [3], here is shown that, even in low S4 levels of scintillation, the performance of π/3-BPSK demodulator can degrade strongly.

In this work, the experiments in the form of computational tests were defined by different link sceneries simulated using a simulation system adapted from [7, 11]. The results, taking into account the fluctuations in amplitude and phase caused by scintillation, shows that the performance of the demodulator in terms of bit error rate and time for acquisition of the carrier can degrade noticeably when compared to results shown in [3].

The main contributions of this work are the estimation of the effects of ionospheric scintillation on UHF links between the DCTs and the satellites of SBCDA, referring some levels of S4 supported by the π/3-BPSK demodulator [3], aiming mainly to increase the QoS of the SBCDA and improvement of the DCTs localization service using satellites [12, 13].

This work should also contribute to emphasize the importance of evaluating the ionospheric scintillation effects in new demodulator projects operating in UHF space links. This approach, even if uses simulation, can help the development of new techniques to decrease the effects of scintillation in space links and/or increase the robustness of the receiver before the definition of the final model and respective implementation in hardware.

This work is organized as follows: in Section II is described the scenery of π/3-BPSK communication links, using a signal model with generation of scintillation for simulation by a Matlab/Simulink Platform. In Section III are shown the results of performance using computational simulations including discussions. In Section IV are presented the conclusions of this work and future perspectives.

2. SIMULATION SYSTEM DESCRIPTION

The architecture of the demodulator and the π/3-BPSK link sceneries using AWGN channel in terms of block diagrams and respective equations were presented in [3]. To generate sceneries containing levels of scintillation similar to those found in the ionosphere and study the impact of scintillation events on the performance of the future transponder based on π/3-BPSK modulation [3] the simulation system used in this work is next described.

2.1 SCINTILLATION GENERATOR PARAMETERS

The scintillation generator used to simulate the transionospheric channel in 401MHz is adapted from the statistical generators of scintillation presented in [7, 11]. This simulator can generate I/Q signals with different levels of amplitude and phase similar to those observed in ionospheric phenomena, which correspond to levels of scintillation denominated as S_4 and σ_ϕ. The indexes S_4 and σ_ϕ, respectively, the intensity and phase of scintillation, are defined by the following expressions:

$$S_4 = \sqrt{\frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2}}, \tag{1}$$

where $\langle\,.\,\rangle$ is the average of value I, intensity of the signal, and the phase index of the scintillation is obtained from:

$$\sigma_\phi = std(\delta\phi), \tag{2}$$

where $\delta\phi$ is the detrended phase error [14].

To analyze the synchronism process in a DPLL, one can model the fluctuation in phase and amplitude due to the ionospheric scintillation as a random process $z(t)$ defined as [11]:

$$z(t) = Ae^{j\phi} + d(t), \tag{3}$$

where A is the constant proportional to the amplitude of the signal which arrives at the receiver directly through the line-of-sight, ϕ is a random variable uniformly distributed between $-\pi$ and $+\pi$ and $d(t)$ is the multipath component due to the part of the signal that is dispersed, modelled as a zero-mean stationary Gaussian process with autocorrelation $R_d(\tau) = E[d^*(t)d(t+\tau)]$.

In this work, it is assumed that the magnitude of $z(t)$ in Eq. (3) has Rice distribution [11], with parameter $K = \sqrt{1-S_4^2}/(1-\sqrt{1-S_4^2})$. It is also assumed that the autocorrelation function of the process $d(t)$ is given by $R_d(\tau) = 2\sigma^2 e^{\left(-\beta|\tau|/\tau_0\right)}\left[cos\left(\beta\tau/\tau_0\right) + sin\left(\beta|\tau|/\tau_0\right)\right]$, that corresponds the passage of a white Gaussian noise through a second-order Butterworth filter. Taking into account that the decorrelation time of channel $\tau_0 > 0$ is defined as the value of τ for which $R_d(\tau)/R_d(0)=e^{-1}$, then the cut-off frequency of this filter is proportional to τ [11]. Therefore for analysis when $\beta = 1.2396464$ the bandwidth B_d due to τ of this low-pass filter can be approximated by:

$$B_d = \frac{\beta}{\sqrt{2\pi\tau}}, \tag{4}$$

where the value of τ_0 depends on the signal frequency and for the UHF band equatorial scintillation during night [15] can be determined using the expression:

$$\tau_0 = \frac{0.1f}{250}, \tag{5}$$

where f is the frequency of signal in MHz. For the case in study, $f = 401$ MHz , one obtains $\tau_0 \cong 0.1604\ s$.

2.2 MODEL FOR THE SIGNAL UNDER EFFECT OF SCINTILLATION AND AWGN

The signals transmitted by the DCTs are a carrier with π/3-BPSK modulation, bit rate 400 bps, frequency ~401MHz and bandwidth 60 kHz. Taking into account the original parameters for AWGN channel used in the design of the modulator π/3-BPSK [3], the satellites receive the signals coming from the DCTs with noise whose power spectral density is -173 dBm/Hz, maximum Doppler shift 9 KHz and power in the range -108 to -126 dBm [2, 3], see expression (1) in [3].

However, when taking into account the transionospheric channel the discrete-time model for the signal with modulation and respective effects from scintillation and AWGN at the input of the demodulator can be expressed in the following way:

$$r[n] = \frac{\sqrt{3}A}{2} b[n]\cos(\omega_c n + \theta_s[n]) + \frac{A}{2}\mathrm{sen}(\omega_c n + \theta_s[n]) + w[n], \quad (6)$$

where $A = A_0 \delta A, A_0$ is the amplitude of the transmitted carrier, δA is the amplitude of the scintillation, ω_c represents the discrete frequency of the carrier, $b[n]$ is the signal in baseband, $\theta_s[n] = \theta_0 + \delta\phi[n] + v_D$ is the phase of the received carrier, θ_0 is an unknown phase caused by possible frequency and phase deviation resulting from space link, $\delta\phi[n]$ is the phase of the scintillation, v_D represents a residual of the Doppler frequency coming from frequency estimator of the transponder [2, 3], which has a maximum value of ± 5 Hz, and $w[n]$ is the AWGN with variance N_w.

The demodulator architecture proposed in [3] implements the optimal receiver for the AWGN channel. However, due to errors of the estimates of the parameters of synchronism, as shown in [3], there is a small loss, in terms of bit error rate, when compared with the ideal receiver. In addition to the model and results presented in [3], here, in section III, are shown also the effects of fluctuation of amplitude and phase and the increase in severity of the losses in the performance of the demodulator submitted to the effects of scintillation.

2.3 SIMULATION PLATFORM

Figure 1 presents the generator of the sceneries concerning modelling of simulated links using functional block diagram of the following subsystems: a) a streaming generator of Matlab/Simulink [16] for random bit generation to be transmitted; b) a generator of π/3-BPSK signal, adapted from [4], taking into account the effects of scintillation adapted from [7, 11]; c) a π/3-BPSK demodulator presented in [3]; and d) a BER (Bit Error Rate) measurer from Matlab/Simulink [16].

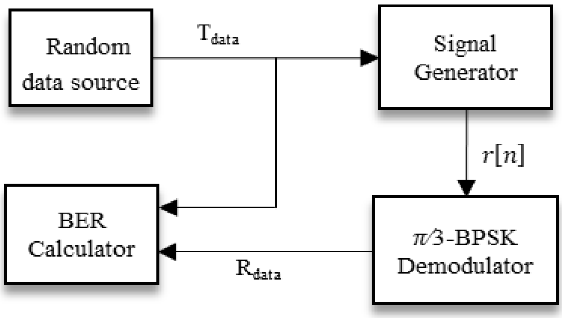

Fig -1: Scheme of the simulation system

The scheme of the simulation system shown in Figure 1 allows to define the setups for several link scenarios, including different conditions of scintillation intensities, and to measure possible impairments in the subsystems of the π/3-BPSK demodulator.

In this context, the Signal Generator in Figure 1 receives the streaming T_data from the Random data source and generates the r[n] signal, Eq. 6, which is sent to the demodulator π/3-BPSK. On its turn, the demodulator delivers the streaming R_data to the BER Calculator and, lastly, using as entries the T_data and R_data, the BER Calculator shows the bit error rate.

The values of the main parameters used in the simulations are summarized in Table 1:

Table -1: Parameters used in the simulations for the testing the π/3-BPSK demodulator [3].

• Carrier frequency: $f_c = 50$ kHz;
• Symbol tax: $1/T = 400$ bps;
• Sampling frequency: $F_s = 200$ kHz ;
• Bit energy per noise density: 5 dB $\leq E_b/N_0 \leq$ 30 dB;
• Carrier acquisition time ≤ 160 ms
• Operating frequency 401 MHz.

3. RESULTS AND DISCUSSION

The section presents performance results of the proposed π/3-BPSK demodulator presented in [3], here taking into account the fluctuations in amplitude and phase, obtained by computational simulation.

3.1 BIT ERROR RATE

Some curves of the bit error rate (BER) of the π/3-BPSK demodulator in AWGN channel are shown in Fig. 6 in [3]. In this work, in Fig. 2, Curve 1 indicates the theoretical performance of the BPSK demodulation. Curve 2 corresponds to the simulated scenery of transionospheric channel with scintillation intensity S_4=0.2, while Curve 3 shows the BER of the demodulator submitted to scintillation S_4=0.3.

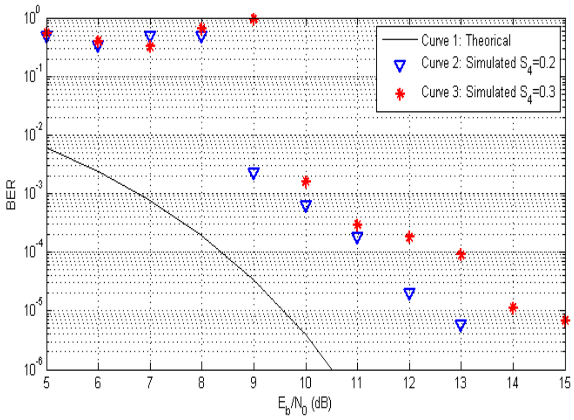

Fig -2: Curves of the bit error rate of the demodulator submitted to scintillation intensities S4=0.2 and S4=0.3.

In the experiments of this work with condition of bit error rate equal to 10^{-4}, the response of the demodulator proposed in [3] compared to the theoretical response suffered a loss of ~3.2 dB for S4=0.2 and ~4.6 dB for S4=0.3. Note that for S4=0.2 there were cycle slips for the interval 5 dB ≤E_b/N_0≤ 8 dB, while for S4=0.3 there were cycle slips for the interval 5 dB ≤E_b/N_0≤ 9 dB in the test time interval t ≥ 60s.

3.2 CARRIER ACQUISITION TIME

Although the results of the BER and synchronization time tests using only AWGN channel (see Figures 6 and 7 in [3]) or S_4≅0.0 are within expected, these new experiments show that the system can be compromised by the acquisition of the carrier as seen in Fig. 3, even when the intensity of scintillation is low (for example S4=0.2). Notice that the recovery time of the carrier in links using that demodulator π/3-BPSK [3] is one of the critical parameters of the transponder (see carrier acquisition time in Tab. 1).

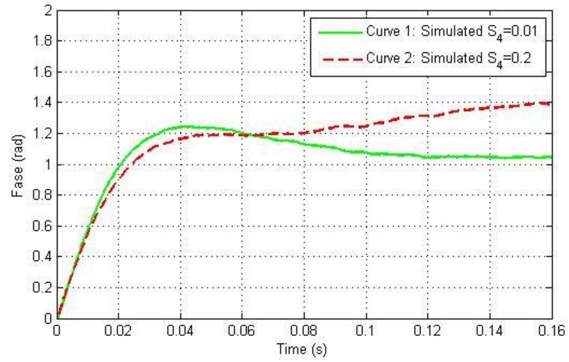

Fig -3: Transitory response of the loop on $\hat{\theta}_c$, output of the discrete-time filter in Fig. 3 in [3], for a phase step taking into account effects of scintillation for S_4=0.01 and S_4=0.2.

Apart from the results presented in Figures (2) and (3), many other tests were made using 15 dB ≤ E_b/N_0 ≤ 30 dB. In the experiments taking into account effects of scintillation, there were no cycle slips for S_4=0.4 using 16 dB ≤ E_b/N_0 ≤ 30 dB. However, there were cycle slips for S_4≥0.5 and E_b/N_0 ≤ 30 dB.

4. CONCLUSIONS AND PERSPECTIVES

In this article, some estimates of possible degradation in performance of the coherent π/3-BPSK demodulator [3] due to distortions caused by the simulated scintillation were presented.

The results of the simulations without scintillation presented in [3] shown that, for the AWGN channel, the solutions used for carrier recovery and symbol synchronizer allow synchronization of the system in smaller time than that which was specified and provoking small impact on the E_b/N_0 relation. However, the new experiments, when the effects of ionospheric scintillation are taken into account, show that the scintillation can cause noticeable degradation in the performance of the demodulator as seen in section III.

In the worst operational situation without scintillation even when there is frequency offset and symbol delay the error of the proposed demodulator [3] in terms of BER is smaller than 1.0 dB when compared to the theoretical limit in the condition BER=10^{-4}. However this article shows that when scintillation is present the loss of the demodulator can reach ~4.6 dB for S4=0.3 in the condition BER=10^{-4}. Note that for S4≥0.5 there were cycle slips even in conditions of E_b/N_0=30 dB. Besides, even taking into account a low intensity of scintillation, for example S4=0.2, the acquisition of the carrier can be compromised.

The architecture of the demodulator π/3-BPSK [3] is inspired on the QPSK demodulator [17, 18]. Assuming the hypothesis presented in [3], taking into account only the AWGN channel, robustness is observed when α is smaller than π/10, see expressions (6), (7) and (8) presented in [3], or α≪1, applied to expression (12), about DPLL on Fig. 3 in [3]. However, in this work, according to the results of the experiments and analysis during the simulations, it was noted that π/3-BPSK demodulator [3] when there is scintillation could also suffer noticeable perturbation in terms of cycle slips and carrier acquisition.

Therefore, although the original design of the demodulator demonstrates that the architecture proposed in [3] shows good performance operating in AWGN channel, before embarking a new transponder on the satellite new studies are being made aiming improvements of the architecture proposed in [3] taking into account the effects of ionospheric scintillation.

The authors hope that the development of possible strategies to decrease the effects of ionospheric scintillation applied to a new version of the demodulator may also benefit designs of other receivers or transponders, for example those presented in [7, 8, 15] and in research applied to the GNSS [19].

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