Impact of Optical Preamplifier Beat Noise on Inter-Satellite Coherent Optical Communication System

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Abstract: The performance of Inter-Satellite coherent optical communication systems is partly limited by the beat noise between the amplified spontaneous emission (ASE) noises and local oscillator. In order to improve the optical detection sensitivity in inter-satellite optical communication links, a model of inter-satellite coherent optical communication is established. And the origin of noise in this system with optical pre-amplifier is investigated. The impact of optical pre-amplifier key parameters on performance of inter-satellite coherent optical communication systems is discussed. Besides, bit error rate (BER) versus signal power, noise figure and gain are numerically calculated. The results illustrated that it is effective to improve the optical detection sensitivity and degrade the bit error rate using an optical pre-amplifier with low noise figure.

1 INTRODUCTION

Optical communication in space is an attractive and available alternative to classical RF communication. Optical space communication systems have the potential for substantially higher data rates than RF-based solutions with similar onboard mass, volume and power consumption. Besides, optical space communication does not require frequency regulation and provides inherently secure data links by means of a high beam directivity (Björn Gütlich, 2013; Patricia Martin-Pimentel, 2014).

Several optical space communication missions have been successfully demonstrated and verified in the recent past, and are today used in commercial system (F. Heine, 2015; Daniel Troendle, 2014; Mark Gregory, 2012).

Nowadays, inter-satellite coherent optical communication draws more research interests as a coherent BPSK data transmission at a data rate of 5.625 Gbps has been performed in-orbit between satellite NFIRE and satellite TerraSAR-X (B. Smutny, 2008).

In the inter-satellite coherent optical communication system, the optical preamplifier could provide the higher gain and detection sensitivity. However, as the introduction of optical preamplifier, which enhances the system performance but brings a new challenge. That is the beat noise between the amplified spontaneous emission (ASE) noises from optical preamplifier and local oscillator (LO), reducing the received signal-to-noise ratio (SNR) (P. C. Becker, 1999).

As far as we know, there are not many literatures examining the impact of beat noise on Inter-Satellite Coherent Optical Communication System systematically.

In this paper, we first describe the mathematical expression of beat noise between the ASE noise and LO in an inter-satellite coherent receiver. Subsequently, the impacts of different parameters on the system’s performance are investigated.

2 SYSTEM SETUP AND NOISE ANALYSIS

2.1 System Setup

A system setup of an inter-satellite coherent optical communication link is showed in Figure 1. The coherent receiver is homodyne BPSK synchronous receiver. In the inter-satellite link, the main noise to impair the system includes the beat noise induced by LO and ASE noises, shot noise, thermal noise, and background noise. Throughout this paper, all the parameters used in analysis are listed in Table 1 unless specified.

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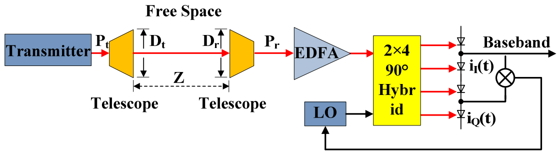

Figure 1: System setup of an inter-satellite coherent optical communication link.

Table 1: Parameters used in the calculation.

Optical Wavelength(λ)	1550nm
Range(Z)	40000km
Transmit Power(P_t)	30dBm
Transmit telescope Diameter(D_t)	15cm
Receive telescope Diameter(D_r)	30cm
Transmit/ Receive efficiency(τ_T)	0.8
Thermal Noise temperature(T)	300K
R	50Ω
RIN	-145dB/Hz
Optical Bandwidth (B_o)	10GHz
Electrical Bandwidth (B_e)	7.5GHz
coupler efficiency(η_c)	0.8

The input signals to a coherent receiver consist of signal $E_s(t)$, LO $E_{lo}(t)$ and ASE noise $E_{sp}(t)$ (N.A.OLSSON, 1989; Hongbo Lu, 2010; J.G.Proakis, 2000), which are represented by:

$$E_s(t)=\sqrt{GP_r}\cos(\omega_s t+\varphi_s) \quad (1)$$

$$E_{lo}(t)=\sqrt{P_{lo}}\cos(\omega_{lo} t+\varphi_{lo}) \quad (2)$$

$$E_{sp}(t)=\sqrt{N_0\delta\upsilon}\sum_{k=-M}^{M}\cos[(2\pi(\upsilon_s+k\delta\upsilon)t+\varphi_k)] \quad (3)$$

$$N_0=n_{sp}(G-1)h\upsilon \quad (4)$$

$$M=B_0/2\delta\upsilon \quad (5)$$

where P_r and P_{lo} represent power of signal and LO respectively, φ_s and φ_{LO} denote optical phase of signal and LO respectively , G is amplifier gain, n_{sp} is noise figure, h is the Planck constant, v is optical carrier frequency. φ_k is a random phase for each component of spontaneous emission. In equation 5, B_o is optical Bandwidth and δv is an arbitrarily small frequency width and is chosen so that M is an integer value.
The recovered inphase and quadrature signals can be easily shown as

$$i_I(t)=\frac{1}{4}R\begin{bmatrix}\left|E_s(t)+E_{sp}(t)+E_{lo}(t)\right|^2\\ -\left|E_s(t)+E_{sp}(t)-E_{lo}(t)\right|^2\end{bmatrix}+i_{sh}(t) \quad (6)$$

$$i_Q(t)=\frac{1}{4}R\begin{bmatrix}\left|E_s(t)+E_{sp}(t)+jE_{lo}(t)\right|^2\\ -\left|E_s(t)+E_{sp}(t)-jE_{lo}(t)\right|^2\end{bmatrix}+i_{sh}(t) \quad (7)$$

2.2 Noise Analysis

In the coherent receiver, the variance of the beat noises between LO and ASE noise is given by

$$N_{lo\text{-}sp}=4R^2P_{lo}N_0B_e \quad (8)$$

where R is the responsivity, B_e is electrical bandwidth.
The variance of shot noise is written as

$$N_{shot}=2eRB_e(N_0B_o+GP_r+P_{lo}) \quad (9)$$

where e is electron quantity.
The variance of thermal noise is given by

$$N_{th}=4k_bTB_e/R_L \quad (10)$$

where k_b is Boltzmann constant, R_L is equivalent resistance, T is temperature, and RIN is relative intensity noise.
For the inter-satellite link, the background radiation is a shot noise with variance as

$$N_{bg}=2eRB_e(P_{sky}+P_{sun}) \quad (11)$$

where P_{sky} and P_{sun} represent the background irradiance of the Sun and the sky respectively.
Consequently, the electrical SNR in the considered coherent receiver has the expression as

$$SNR=\frac{R^2GP_rP_{lo}}{N_{lo\text{-}sp}+N_{shot}+N_{th}+N_{bg}} \quad (12)$$

To investigate the BER of BPSK for homodyne detection, its analytical BER is calculated by equation (13), where the probability density function $p(\Delta\varphi)$ of phase noise is assumed to be Gaussian-distributed with mean zero.

$$BER=\frac{1}{2}\int_{-\pi}^{\pi}erfc\left[\sqrt{SNR}\cdot\cos(\Delta\phi)\right]p(\Delta\phi)d(\Delta\phi) \quad (13)$$

3 NUMERICAL RESULTS

First we calculate the SNR of system versus preamplifier gain with noise figure as parameter. In the calculation, the received power P_r is -40dBm and LO power P_{lo} is 10dBm. As shown in Figure 2, the SNR of the system is monotonically increasing as the surge of preamplifier gain, but gradually reach saturation. This can be mainly attributed to both the received power and the LO-ASE beat noise increase as the surge of preamplifier gain. It is not used for *G*=10dB because of the SNR is less than 6dB. And it is also no enhancement for SNR while the preamplifier gain reaches to 30dB.

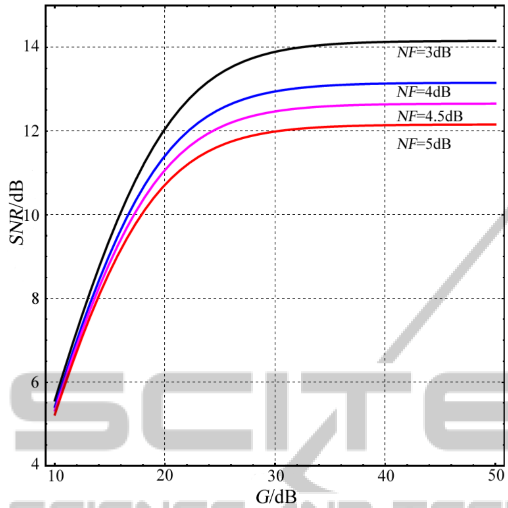

Figure 2: SNR versus gain of preamplifier with different noise figure. (NF=5dB red line, NF=4.5dB magenta line, NF=4dB blue line, NF=3dB black line).

Then we calculate the BER versus preamplifier gain with noise figure as parameter. The results are shown in Figure 3.The BER of the system is decreasing as preamplifier gain increasing, but gradually reach a minimum. It is worthy to know that the BER is 10^{-10}, 10^{-9}, 10^{-8} for the NF of 4dB, 4.5dB and 5dB, respectively when the gain larger than 30dB. The BER will be increasing an order as the NF grows up 0.5dB.

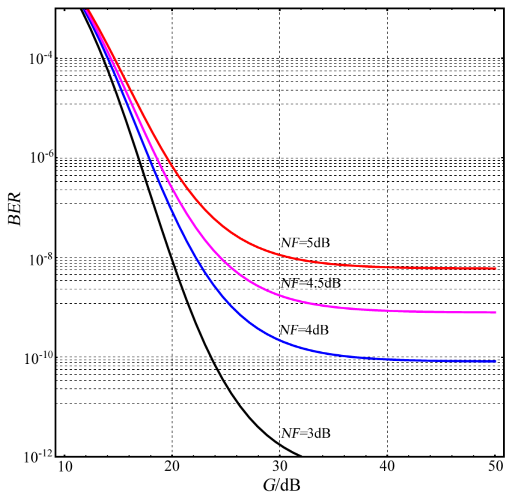

Figure 3: BER versus gain of preamplifier with different noise figure. (NF=5dB red line, NF=4.5dB magenta line, NF=4dB blue line, NF=3dB black line).

We set noise figure at the value of 4.5dB, and calculate BER versus receive power P_r with preamplifier gain as parameter. As the results shown in Figure 4, the sensitivity will be enhanced 1.5dB when the BER is 10^{-9} for comparing the gain of 20dB and 30dB. It is possible to enhance the sensitivity via increasing the preamplifier gain with the same noise figure to maintain BER.

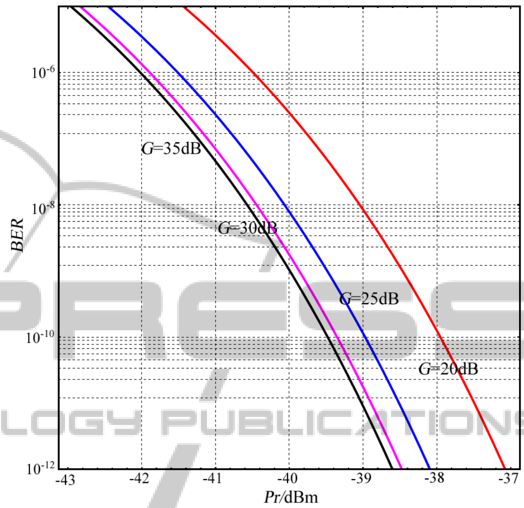

Figure 4: BER versus received power with different gain. (G=20dBm red line, G=25dB magenta line, G=30dB blue line, G=35dB black line).

BER versus NF with different gain are calculated and illustrated in Figure 5. The BER is monotonically increasing as the surge of NF. It is possible to decrease the BER via increasing the gain if the NF maintains constant.

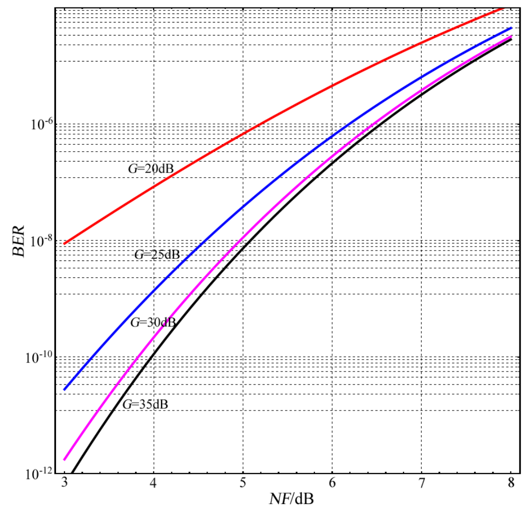

Figure 5: BER versus NF with different gain. (G=20dBm red line, G=25dB magenta line, G=30dB blue line, G=35dB black line).

As shown in Figure 6, it also concludes that we could enhance the sensitivity via increasing the preamplifier gain if the BER maintains constant.

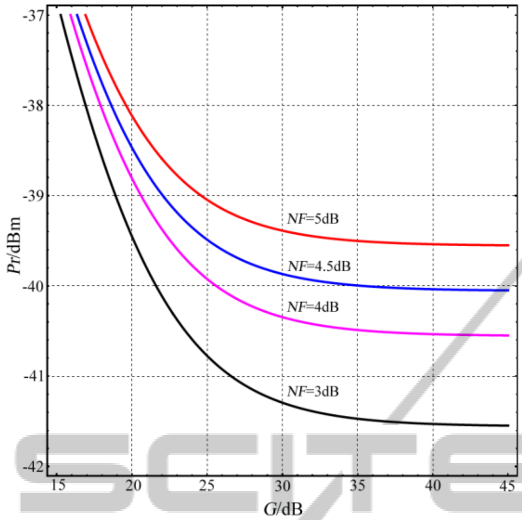

Figure 6: Received power Pr versus gain with different noise figure. (NF=5dB red line, NF=4.5dB magenta line, NF=4dB blue line, NF=3dB black line).

We last calculate BER versus the rms phase error with noise figure as parameter. And we set the gain at the value of 30dB. The results are shown in Figure 7. In order to maintain BER at 10^{-9} and the rms phase error less than 0.175rad, it shows that the noise figure should less than 4.5 dB if the gain is 30dB.

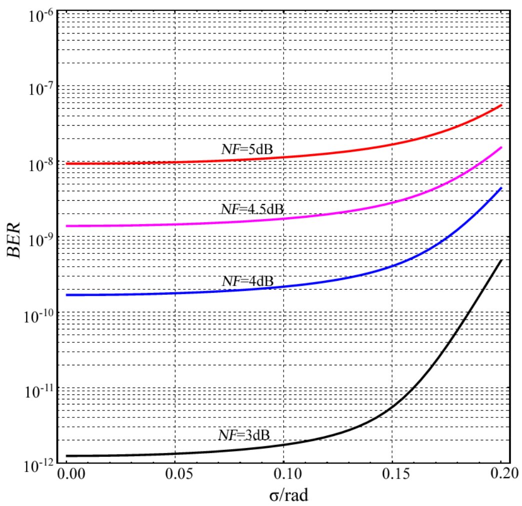

Figure 7: BER versus rms phase error with different noise figure. (NF=5dB red line, NF=4.5dB magenta line, NF=4dB blue line, NF=3dB black line).

4 CONCLUSIONS

We have studied the impact of optical preamplifier ASE beat noise on an inter-satellite coherent optical communication system. It is numerically shown that the presence of preamplifier would enhance the received sensitivity at a certain LO power level.

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