The Laser Satellites Communications and Laser Noises

MARKETA MAZALKOVA
Communication and Information Systems Department
University of Defence
Kounicova 65, 612 00 Brno
CZECH REPUBLIC

Marketa.Mazalkova@unob.cz, http://fvt.unob.cz/article.asp?key=452&m=13&s=65

Abstract: - The gain of advanced optical communication systems is reduced by the noise of optical source. Coherent optical communication systems are in particular very sensitive to the noise transmitter and local laser. Optical space communications is on the verge of being reality. The paper involves the introduction into laser satellite communication system. The paper includes briefly analysis, optimization, design and system level development of signal transferring between satellites. Research opportunities in this area include development of laser beam acquisition, tracking and pointing techniques and algorithms, development of computer aided analysis link budget for the free space channel, systems engineering (analysis and design) of optical transmission development of high efficiency flight qualifiable solid-state lasers, fast fine-pointing mirrors high update-rate acquisition and tracking cameras and very low-noise high-quantum efficiency receiver. It is focused on the noises' limits of the optical communication system. The paper solves the problems with noises' limits by various ways. There are mentioned the optical energy output on an aperture's spread of optical detector and incoherent detection of optical carrier wave.

Key-Words: - laser, satellite systems, laser communication, space channel, noise limits, optical communication, range loss, signal transfer loss, satellite communications

1 Introduction

The optical space communications are a key building block for wide-area space data networks. A crosslink, or communication between two satellites, may be needed to solve certain requirements of satellite communication architecture. Laser communications offers the user number of unique advantages over radio frequency (RF) systems, including size, weight, power and integration ease on the spacecraft. Integration ease issues include compactness of terminals, elimination of complex frequency planning and authorization, and RF interference issues [1].

Laser crosslinks will be enable the transfer of data between satellites at rates compatible with ground fiber networks. This is an exciting era for space laser communications. Not only is information transfer driving the requirements to higher data rates, but laser crosslink technology explosions, global development activity, and increased hardware/design maturity are all contributing to interest in space laser communication [2].

2 The laser satellite system

The optical communication systems become more and more attractive as the interest in high-capacity and long-distance space links grows. Advancer in laser communication system architectures and optical components technology make such high capacity links feasible. The laser communication equation (LCE) is a basic resort of LICS's (Laser Inter-satellite Communication System) analysis. Based on the background and receiver noise and the type of signal modulation which is to be detected, a required signal is generated. The ratio of received signal to required signal is the system link margin. Identifying these gains and losses requires intimate knowledge of the system design, including both the internal constraints and design choices and knowledge of the external factors, including range, data rate, and required signal criteria. These parameters are of single-way data transfer for three independent links – acquisition, tracking and data transfer *fig.1*.

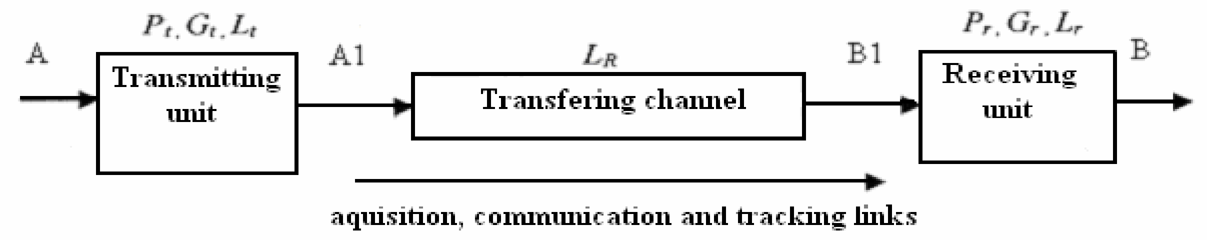

Fig.1 The model of signal transfer in LICS

2.1 The laser communication equation

This equation is used for analysis and optimization.

The equation starting with the transmit source power, the designer identifies all sources of link degradation (losses) and improvements (gains) and determines the received signal level. The laser communication equation (LCE) is very analogous to the link equation for any RF communication link. The link equation can be written as

$$P_r = P_t G_t L_t L_R G_r L_r \quad (1)$$

where:
P_r…the receive signal power (dB),
P_t…the transmitted signal power (dB),
G_t…the effective transmit antenna gain (dB),
L_t…the efficiency transmitter loss (dB),
L_R…the free space range loss (dB),
G_r…the receive antenna gain (dB),
L_r…the efficiency loss associated with the receiver (dB),
A…data from information supply,
A1…coded and modulated optical signal,
B1…optical signal before detection,
B…data for user [2].

There are determined signal sources, improvements (gains) and link degradation (losses) in this communication equation. The definitions of all parameters are not in this paper, but each entry into the link equation is given and verified in [3].

2.1.1 The free space range loss

The link range loss results from the diverging wave front of the optical energy as it traverses the link distance. The calculation of the classical range loss is given by

$$L_R = 10\log_{10}\left[\frac{\lambda}{4\pi R}\right]^2 \quad (2)$$

where:
λ...the wave length (nm),
R...the range between satellites.

LICS parameters premises are optimized by computer programme, the premises consider two satellites in an orbit. For satellites at an altitude h above the Earth's surface and traversing circular orbits, the range between satellites is given as

$$R = \sqrt{2.(R_z + h)^2 + 2.(R_z + h)^2.(1-\cos(\beta))} \quad (3)$$

where:
R_z… the Earth radius (m),
h… the altitude above the Earth's surface (m),
β… the orbital angle between two satellites.

Receive antenna gain is calculated from the antenna gain is calculated from the collecting area of the antenna and the wavelength of the incident optical energy and is expressed by a unitless parameter as

$$G_r = \left[\frac{\pi D_{aper}}{\lambda}\right]^2 \text{(-, m, m)} \quad (4)$$

where:
D_{aper} …the aperture diameter.

Receiver optical losses - before the optical transmission at the wavelength of operation is required to be estimated using good design practices, superior optical coatings, and the number and type of optical surfaces being traversed. Each optical surface contributes a multiplicative loss factor to the overall transmission budget. This loss factor degrades the transmit power by the derived factor.

Receiving pointing loss – similar to the loss associated with the transmitter pointing error, a loss term must be considered for the mispointing at the receiver. For direct-detection links, this is normally not a concern since the receive FOV and spot size are oversized and not diffraction-limited.

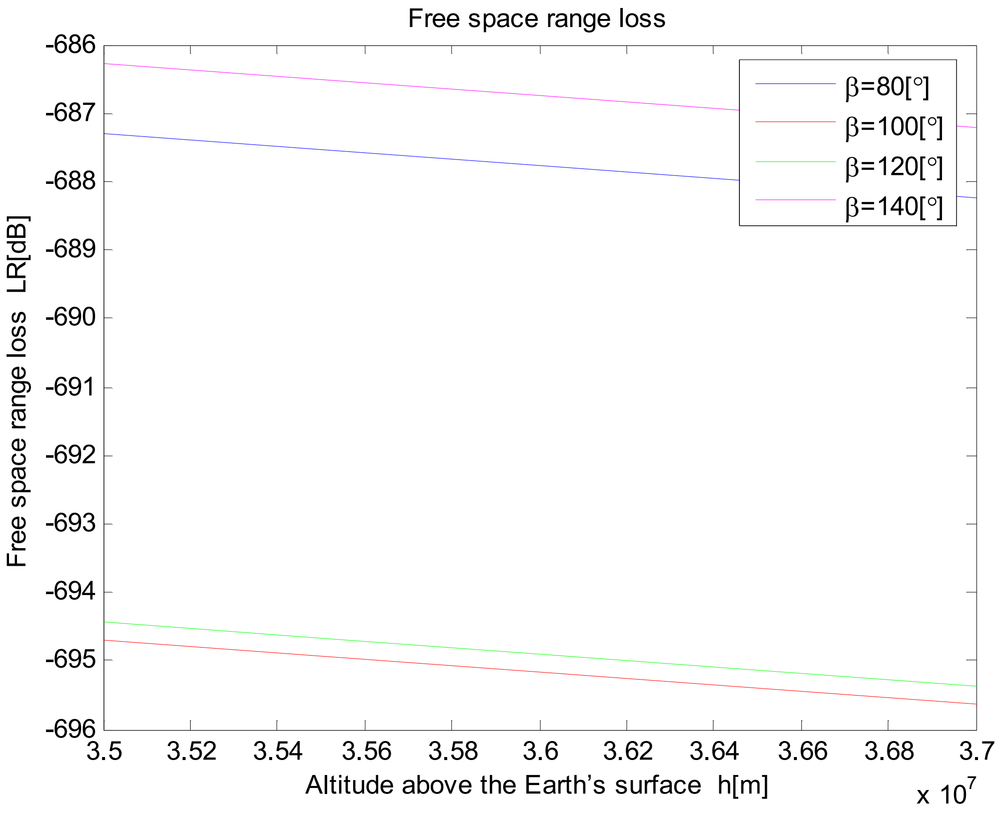

Fig. 2 Free space range loss

3 Laser noise

3.1 Acquisition link

Acquisition requires searching the uncertainty area to locate and establish the link between satellites.

The convergence link is not dominated by the excess communication channel shot noise, as the tracking link. The difference in required signal when the communication channel excess noise is removed is on the order of 3 dB.

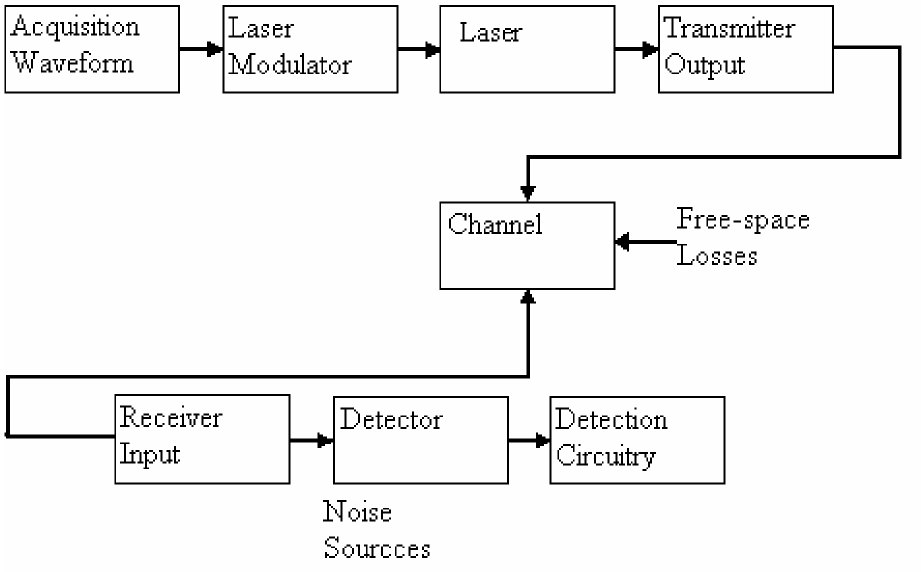

Fig. 3 Acquisition link model

The square root of the laser powers yields the divergence widening factor is

$$F_{DIV} = \sqrt{1.93.\frac{P_{t-com}}{P_{t-trk}}} \quad \text{(-, W, W)} \qquad (5)$$

where:
$P_{t\text{-}com}$ … the maximal power of laser sources,
$P_{t\text{-}trk}$ … the power of sourceof the tracking link.
Detector responsivity is calculated from:

$$Rd = \frac{nq\lambda}{hc} \quad \text{(A/W,-, C, m, J/sec, m/sec)} \qquad (6)$$

where:
η…the quantum efficiency,
q…the electron charge,
λ…the wavelength,
h…the Planc's konstant.

Acquisition is accomplished using a pilot signal, easily recognizable and detectable receiver. The receiving system must detect line of sight. This takes a few iterations of detections and a reasonable bandwidth of received signal to allow angular control of return beam. The acquisition is affected by free-space range loss.

3.2 Tracking link

The critical figure of merit for tracking links is the noise equivalent angle (NEA). The NEA is defined as the residual tracking error along the line-of-sight vector to the companion satellite. The NEA is the function of the received signal to noise ratio (SNR) in the tracking bandwidth, the optical spot size on the detector, and the gain of the tracking system.

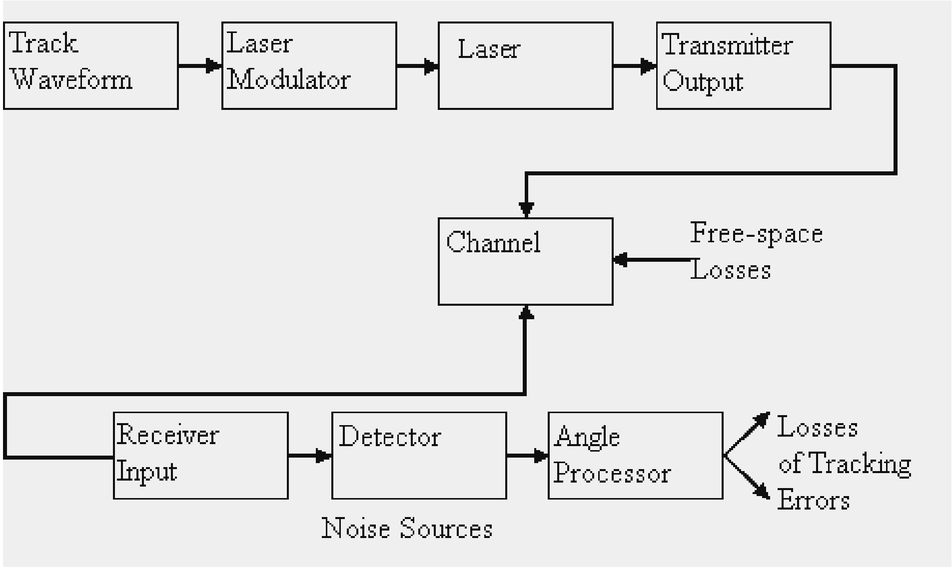

Fig.4 Track link model

The required signal for the tracking system is directly related to the tracking noise established by the budget developed earlier. Based on the required noise equivalent angle and the angle slope factor, the required signal is calculated from:

$$I_{pk-trk} = \frac{2qFB.(1+1/N_e)}{(SF.\sigma_{rms})^2.(1-1/N_e)^2} +$$

$$+\sqrt{\left[\frac{2qFB.(1+1/N_e)}{(SF.\sigma_{rms})^2.(1-1/N_e)^2}\right]^2 +}$$

$$+\frac{4.\sigma_{total-trk}^2.B}{(SF.\sigma_{rms})^2.(1-1/N_e)^2} \qquad (7)$$

where:
q…the quantum charge,
F…the noise factor of the detection process,
B…the electrical bandwidth,
N_e…the extinction ratio for a square-wave tone,
SF…the angular slope factor,
σ_{rms}…the noise equivalent angle NEA,
$\sigma_{total\text{-}trk}$…the total noise density for tracking.

$$P_{t-trk(dB)} = P_{r-trk(dB)} - \begin{pmatrix} G_{t(dB)} + (\sigma_{ur})_{(dB)} + L_{wf(dB)} + \\ L_{t(dB)} + L_{R(dB)} + G_{r(dB)} + L_{r(dB)} \end{pmatrix} \quad (8)$$

where:

$P_{t\text{-}trk}$…the transmitted signal power of tracking ling,

$P_{r\text{-}trk}$…the received signal power of tracking link.

3.3 Communication link

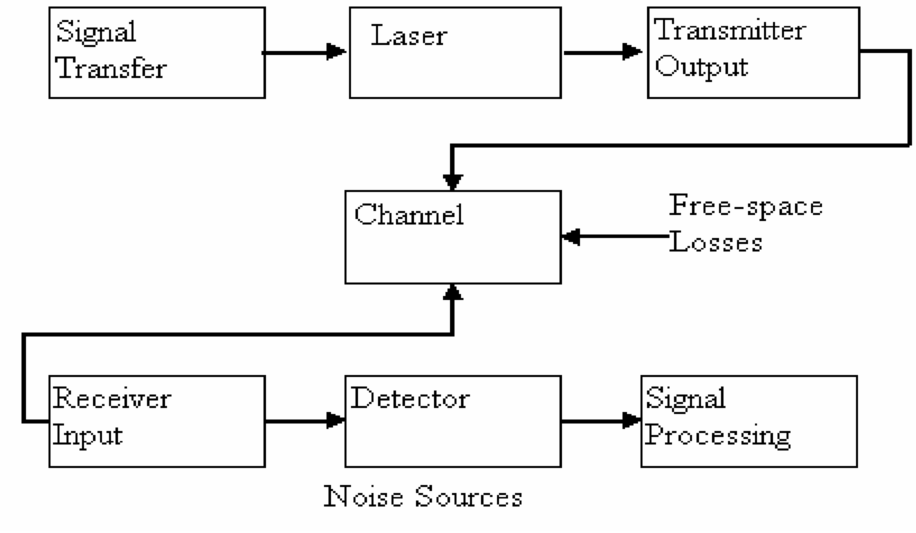

Fig.5 Communication link model

This is a link for the data transfer from one satellite to its companion. Optical source and modulation have to be carefully examined to determine best modulation approach for each source. The receivers have to be matched to the type of modulation used.

3.4 Laser noise

The gain of advanced optical communication systems is reduced by the noise of optical source. Coherent optical communication systems are in particular very sensitive to the noise of transmitter and local laser. In optical communication links employing an LED, transmitter noise is normally negligible in comparison to the other sources of noise in the system such as shot noise of photodiodes and thermal noise of resistors and electrical amplifiers. Laser noise, laser intensity noise and laser phase noise is only negligible in communication systems with moderate bit rate and moderate transmission length. However, laser intensity noise can seriously degrade the quality of transmission in high bit rate links and laser phase-locked loop (PLL). Unlike coherent detection, conventional optical communication systems with intensity modulation of light and direct detection (IM/DD) are absolutely intensive to laser phase noise. This is a significant advantage of using direct detection systems instead of coherent detection systems.

Modulation in direct detection system is easily performed by tuning the laser light on and off as per the digital binary information signal to be transmitted. Hence, this kind of modularion is usually called on-off keying (OOK) or in a more devaluated way “smoke-sign modulation”. A special knowledge of laser physics is not required and sample black-box consideration of laser source is quite adequate for such applications.

In an ideal laser, transmitted optical wave is composed of simulated emission only, spontaneous emission processes does not occur. Therefore, an ideal single-mode laser transmits a real monochromatic light wave with a single frequency $f_a \rightarrow f_0$ only and, in addition, a time-invariant constant phase $\Phi_a \rightarrow \Phi_0$. The mode number a as a special index is no longer required. Instead, we use the new index “0” to represent a laser that operates without any laser noise (zero noise). In the ideal case, power spectral density or emission spectrum $G_a(f) \rightarrow G_0(f)$ of a single-mode laser is completely defined by a Dirac delta function.

Laser noise arises from spontaneous emission processes which are unavoidable in a laser. In gas lasers, physical reason of spontaneous emission is primarily the local fluctuations of laser mirrors. These fkuctuations are in turn caused by the changes in temperature and external mechanical disturbances.

In a single-mode laser with discrete energy states, spontaneous emission as well as stimulated emission only generate optical waves at frequency f_0. Phases of the stimulated waves are all synchronous, whereas they are random and absolutely uncorrelated in case of spontaneously emitted light waves.

4 Optical receiver

The scope factor depends on noises' limits. They are given by different factors. This paper shows more details from this area.

In an optical communication system, the function of the receiver is to convert a received optical signal into an electrical signal, which can serve as an input for other devices or communication systems.

The optical receiver basically consists of a receiving optics followed by a demodulator/detector. The latter may be based on incoherent or coherent techniques depending upon the type of modulation scheme used [4].

4.1 The detector's optical power

The receiver in a direct detection, diameter of the receiving antenna should be as large as possible to gather the maximum amount of signal energy [5].

4.1.1 The minimal value of power of receiving at the input of optical detector

The minimal value for this parameter is given as

$$P_{C\min} = \frac{\pi^2 \tau_t \tau_a \tau_r d_T^2 d_R^2 P_L}{32 R^2 \lambda_c^2} \tag{9}$$

where:
τ_t…the coefficient of the transfer of transmitting subsystem,
τ_r…the coefficient of the transfer of receiving subsystem,
$\tau_a = \tau_{FS}$…the coefficient of the free space transferring,
d_T… the aperture diameter of the transmitting system,
d_R…the aperture diameter of the receiving system,
P_L…the laser power,
R…the range between transmitting and receiving units,
λ_c…the optical wavelength of the carrier.

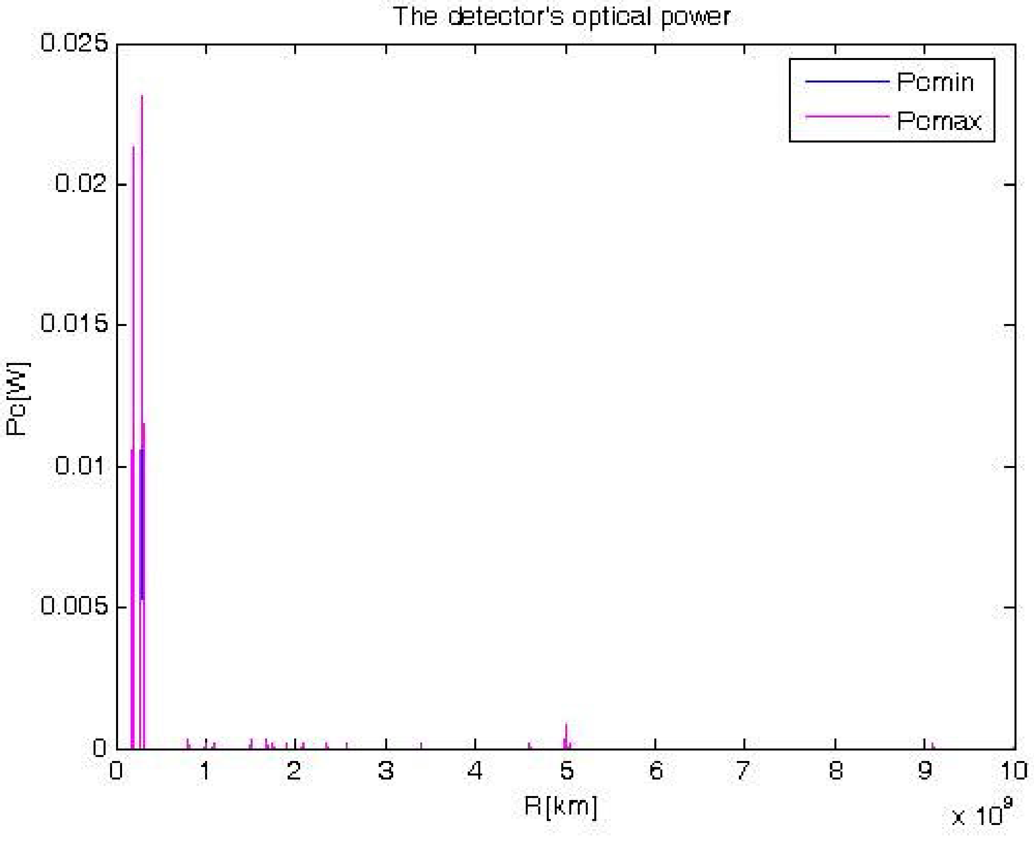

Fig. 6 The comparison of minimal and maximal value of power of receiving optical detector

4.1.2 The maximal value of power of receiving at the input of optical detector

The maximal value for the power of receiving of optical detector can be characterized by

$$P_{C\max} = \frac{\pi^2 \tau_t \tau_a \tau_r d_T^2 d_R^2 P_L}{16 R^2 \lambda_c^2} \tag{10}$$

There is a graphical output of comparison these parameters in figure 6.

4.2 Incoherent direct detection of optical carrier

The photodetectors used in optical space communications include PIN-photodiode, avalanche photodiode (APD), photomultiplier tube (PMT) and photon counter. These detectors have their own merits and demerits.
For direct detection inter-satellite links based on Nd: YAG laser, detector used is either a PIN-photodiode or an APD [6].

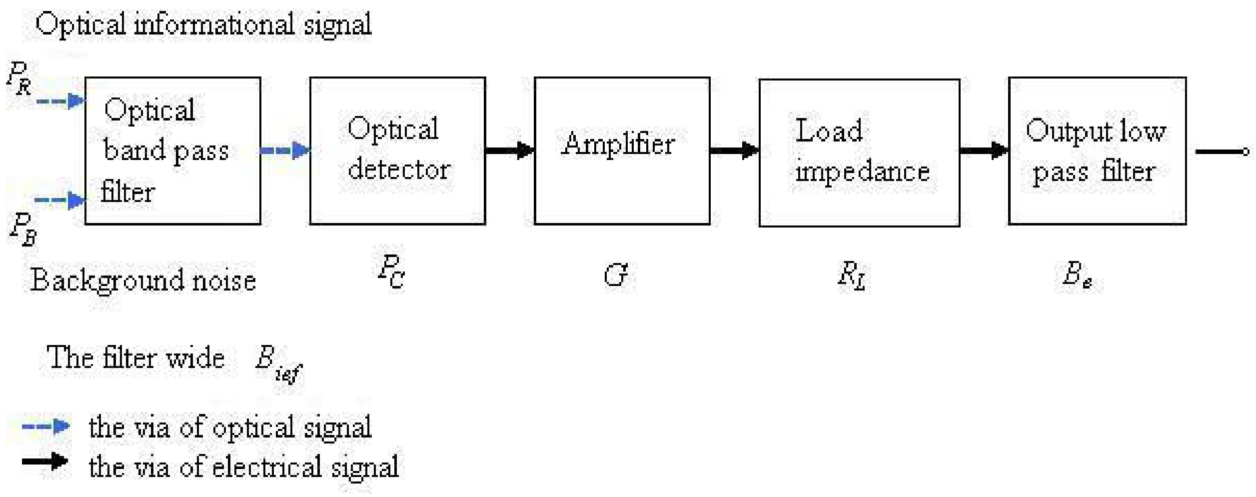

Fig.7 The schematic diagram of optical communication receiver – direct detection

4.3 Problem Solution

$B_0=B_e$… the electrical bandwidth

The signal power S without modulation is given as

$$S = \frac{v_S^2}{R_L} = (G\alpha P_c)^2 R_L \tag{11}$$

where:
v_s…the signal output from the circuit (the signal, which we can get after passing the output low pass filter),
R_L…the load resistance,
G…the circuit gain,
P_c…the power of receiving detector,
α…the coefficient of transformation.

This coefficient of transformation can be written as

$$\alpha = \frac{\eta q}{h f_c} = \frac{\eta q \lambda_c}{hc} \tag{12}$$

where:
η…the efficiency,
q…the electronical charge,
h…the Planc constant,
f_c…the frequence of the carrier,
λ_c…the optical wavelength of the carrier,
c…the speed of light [7].

4.4 The noise in photodiodes

The main sources of noise are dark current noise, shot noise and thermal noise in a photodiode. There is one more source of noise due to random nature of the avalanche in an APD.

The dark current noise arises due to dark current which flows in the circuit when the photodiode is in unilluminated environment under bias condition. It is equal to the reverse saturation current of the photodiode. The magnitude of this current is strongly dependent on the operating temperature, the bias voltage and the type of detector. In an optical receiver, dark current sets a noise floor for the detectable signal power level. Therefore, it should be minimized by careful device design and fabrication. Dark current in optical telecommunication grade Si PIN-photodiodes is typically 100pA, while in Si APDs it is typically 10 pA. In InGaAs based PIN-photodiodes and APDs, the dark current is of the order of 100nA and it could pose a serious problem unless the device is cooled an appropriate temperature.

The shot noise arises from the statistical nature of the generation and collection of the photoelectrons when an optical signal is incident on photodiode. These statistics follow a Poisson process. Since the fluctuations in the number of photo-carriers generated from the photoelectric effect are a fundamental property of the photo-detection process, it will always exist. It thus set the lower limit on the receiver sensitivity when all other conditions are optimized. If dark noise current is large copared to signal current, signal current may be masked by the noise and therefore becomes unusable. On the other hand, if dark noise current is relatively small, it may have a negligible effect.

The thermal noise originates within the photodiode load resistance. Electrons within any resistors never remain stationary. They continuously move because of their thermal energy even with no applied voltage. The electron motion is random, so the net flow of charge could be towards one electrode or the other at any instant. Thus, a randomly varying current exists in the resistor [8], [9], [10].

4.4.1 The powers of noises

There is an equation for the calculation of the power of the shot noise:

$$N_H = 2qG^2\left(I_P + I_B + I_D\right)B_e R_L \tag{13}$$

where:
q… the electronical charge,
G…the circuit gain,
I_P…the primary photocurrent,
I_D…the dark current,
B_e…the electrical bandwidth,
R_L…the load resistance,
I_B…the background current which can be given as

$$I_B = \alpha P_B \tag{14}$$

where:
α…the coefficient of transformation,
P_B…the background power.

Johnson's definition of the thermal noise can be simply written as:

$$N = N_H + N_T \tag{15}$$

where:
N…the total noise,
N_H…the shot noise,
N_T…the thermal noise.

The signal to noise ratio is one of the most important parameters of the communication system. The value of this parameter can be optimized, but it is very difficult.

$$\frac{S}{N} = \frac{\left[\frac{G\eta q}{hf_c}\right]^2 R_L P_C^2}{2qB_e G^2\left\{\frac{nq}{hf_c}\left[P_C + P_B\right] + I_D\right\}R_L + 4kTB_e}$$

(16)

where is only a one unknown parameter:
T…the temperature of the system.

There can be three different relation for each of three different situation.

The first is: $N_T \gg N_H$, G=1:

$$\frac{S}{N} = \left[\frac{\eta q}{hf_c}\right]^2 \frac{R_L P_c^2}{4kTB_e} \tag{17}$$

The second is: $N_H \gg N_T$, G>>1:

$$\frac{S}{N} = \left[\frac{\eta}{hf_c}\right]^2 \frac{q}{2B_e} \frac{P_C^2}{\left\{\frac{nq}{hf_c}\left[P_C + P_B\right] + I_D\right\}} \tag{18}$$

The last is: P_B=0: it is theoretical situation for non-existing background optical power

$$\frac{S}{N} = \frac{\eta P_C}{2hf_c B_e} \tag{19}$$

4.4.2 Incoherent direct detection (APD)

The shot noise is:

$$N_H = 2q\left(\alpha P_C\right)G_{APD}^{(x+2)}B_e \tag{20}$$

The laser noise is:

$$N_L = 2qI_{LAPD}B_e \tag{21}$$

The detector noise is:

$$N_D = 2qI_D G_{APD}^{(x+2)}B_e \tag{22}$$

The transmitter noise is:

$$N_T = \frac{4kTB_e F_T}{R_L} \tag{23}$$

where:
I_{LAPD}...the surface current,
G_{APD}…the gain of APD,
F_T…the noise figure of the electrical circuits.

The signal to noise ratio for APD is given as

$$\left(\frac{S}{N}\right)_{APD} = \frac{\left(\alpha P_C G_{APD}\right)^2}{2q(\alpha P_C + I_D)G_{APD}^{x+2}B_e + 2qI_{LAPD}B_N + 4kTB_e F_T / R_L}$$
(24)

5 Mathematical and physical implementation analysis and optimization of inter-satellite communication system in MATLAB

Bearing in mind the main research objective, partial goals have been defined. These goals include mathematical and physical analysis of basic parameters and characteristics for LICS design that is required for communication and control signals transfer between GEO satellites. This analysis is also needed for LICS technological basis design. Finally, it is also necessary for computer implementation of several-parametric correlation into analysis and optimization in MATLAB programme. Analysis and optimization is given by the graphical outputs that enable LICS parameters optimization occurring in actual situation.

The original research study [3] is over 90 pages long, so it is impossible to mention all relevant data in this paper. It includes a programme for the input parameters design, for the input and output losses, as well as free space losses.

Basic mathematical and physical description aforesaid system aspects are dealt with in research study [1] and they serve as a starting point for computer implementation of several-parametric correlation programme.

The equations which were used in the calculations and in graphical outputs of parametric correlations of LICS system optimization are given at the end of this paper.

The original programme has been prepared in MATLAB. The programme is able to calculate selected several-parametric correlations and to convert them into graphical outputs. We are able to indicate optimal values of selected system transfer parameters according to specified criteria.

6 Conclusion

The original research study [1] is over 90 pages long, so it is impossible to mention all relevant data in this paper. The research study includes mathematical and physical analysis of basic parameters and characteristics for LICS design that is required for communication and control signals transfer between GEO satellites; computer programme for the input parameters design, for the input and output losses, as well as free space losses. The programme is able to calculate selected several-parametric correlations and to convert them into graphical outputs. We are able to indicate optimal values of selected system transfer parameters according to specified criteria.

Mathematical-physical basic description aforesaid system's aspects are in research work and are starting point for computer implementation programme several-parametric correlations [3]. The origin programme is made in MATLAB. The program is able to calculate selected several-parametric correlations and convert them in graphical outputs. We are able to indicate optimal values selected parameters of system transfer by enter criterions.

All parameters were calculated. The analysis and optimization were made from graphical outputs. The values of parameters are different for each links. Analysis and optimization supported by computer programme allow making cost-effective decision in designing individual parameters in laser inter-satellite communication system [4].

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