The Solution of Noises in Systems of Laser Communication Satellites by Artificial Neural Networks

MARKETA MAZALKOVA
Department of Communication and Information Systems
University of Defence
65 Kounicova, 612 00 Brno
CZECH REPUBLIC
Marketa.Mazalkova@unob.cz

Abstract: - Optical space communications is on the verge of being reality. The paper involves the introduction into laser satellite communication system. In the beginning it includes briefly analysis, optimization, design and system level development of signal transferring between satellites – laser satellite’s equation which is the basic principle of whole communication system. In these systems – systems of laser satellites communication are lots of noises. It is focused on the noises’ limits of the optical communication system. The paper solves the problems with noises’ limits by various ways. One of the possibilities of problem resolution is solution due to artificial neural networks as a system for analysis and optimisation input and output parameters of laser satellite communication equation. It involves the introduction into artificial neural networks and description of Hopfield network, which is use for problem solution. There are mentioned the optical energy output on an aperture’s spread of optical detector and incoherent detection of optical carrier wave.

Key-Words: satellite systems, laser communication, space channel, noise limits, optical communication, range loss, signal transfer loss, satellite communications, artificial neural network, Hopfield network.

1 Introduction
The nowadays research of inter-satellite communication is centred on hybrid ordering laser and microwave systems. The laser inter-satellite communication is predicted on real GEO satellites.

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 users 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].

The analysis of laser inter-satellite system is given by studying basic parameters for communication between two satellites on geostationary orbit.

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 inter - satellite system’s parameters
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. This equation expresses the dependences of different parameters, such as source power and gains and losses parameters during signal transfer. These parameters provide relevant data for technological implementation design. 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.

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

\[ P_r(dB) = P_t(dB) - (G_t(dB) + \sigma_{ur}(dB) + L_{sf}(dB)) \]

where: \( P_r \) the receiving signal power (dB), \( P_t \) the transmitting signal power (dB), \( G_t \) the effective transmitting antenna gain (dB), \( \sigma_{ur} \) the receiving antenna gain (dB), \( L_{sf} \) the efficiency loss associated with the transmitter (dB), \( L_{r} \) the efficiency loss associated with the receiver (dB), \( L_{fsf} \) the free space range loss (dB), and \( \sigma_{tr} \) the transmitting pointing loss (dB).

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].

## 3 Laser noise

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. 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.

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

\[ P_{c_{min}} = \frac{\pi^2 \tau r \tau r \tau r \tau r d_{r} d_{r} P_{c}}{32 R^{2} \lambda_{c}^{2}} \]  

where: \( \tau_r \) the coefficient of the transfer of receiving subsystem, \( \tau_r \) the coefficient of the transfer of receiving subsystem, \( \tau_r \) the coefficient of the free space transferring, \( d_{r} \) the aperture diameter of the receiving system, \( d_{r} \) the aperture diameter of the receiving system, \( P_{c_{max}} \) the laser power, \( R \) the range between transmitting and receiving units, \( \lambda_{c} \) the optical wavelength of the carrier.

### 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

\[ P_{c_{max}} = \frac{\pi^2 \tau r \tau r \tau r \tau r d_{r} d_{r} P_{c}}{16 R^{2} \lambda_{c}^{2}} \]  

### 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].

### 4.3 Problem Solution

\( B_{0} = f_{c} \) ... the electrical bandwidth

The signal power \( S \) without modulation is given as

\[ S = \frac{\nu_{c}^{2}}{R_{L}} \left( G \alpha P_{c} \right)^{2} R_{L} \]

where: \( \nu_{c} \) 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, \( \alpha \) the coefficient of transformation.

This coefficient of transformation can be written as

\[ \alpha = \frac{\eta h f_{c}}{\eta q \lambda_{c}} = \frac{\eta q \lambda_{c}}{h} \]

where: \( \eta \) the efficiency, \( q \) the electronical charge, \( h \) the Planck constant, \( f_{c} \) the frequence of the carrier, \( \lambda_{c} \) 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 to 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 compared 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:

\[
N_h = 2qG^2(I_p + I_b + I_D)B_c R_L \tag{8}
\]

where: \(q\)…the electronical charge, \(G\)…the circuit gain, \(I_p\)…the primary photocurrent, \(I_D\)…the dark current, \(B_c\)…the electrical bandwidth, \(R_L\)…the load resistance, \(I_b\)…the background current which can be given as

\[
I_b = aP_B \tag{9}
\]

where:

\(a\)…the coefficient of transformation, \(P_B\)…the background power.

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

\[
N = N_h + N_T \tag{10}
\]

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.

\[
S/N = \frac{\left[\frac{G\eta q}{h\nu c}\right]^2 R_L P_c^2}{2qB_c G^2\left[\frac{nq}{h\nu c}\left[P_c + P_B + I_D\right] + I_b + 4kTB_c\right]} \tag{11}
\]

where: \(T\)...the temperature of the system.

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

The first is: \(N_T >> N_h\), \(G=1\):

\[
S/N = \left[\frac{\eta q}{h\nu c}\right]^2 \frac{R_L P_c^2}{4kTB_c} \tag{12}
\]
The shot noise is:
\[ N_{sh} = 2q \left( \alpha P_C G_{APD}^{(s+2)} \right) B_e \]  
(15)

The laser noise is:
\[ N_L = 2qI_{APD} B_e \]  
(16)

The detector noise is:
\[ N_D = 2qI_D G_{APD}^{(s+2)} B_e \]  
(17)

The transmitter noise is:
\[ N_T = \frac{4kTB_F T}{R_L} \]  
(18)

where: \( I_{APD} \)...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
\[ \left( \frac{S}{N} \right)_{APD} = \frac{2q(\alpha P_C + I_D) G_{APD}^{(s+2)} B_e + 2qI_{APD} B_N + 4kTB_F T}{R_L} \]  
(19)

5 Artificial Neural Networks

An artificial neural network is a system based on the operation of biological neural networks, in other words, is an emulation of biological neural system. Although computing these days is truly advanced, there are certain tasks that a program made for a common microprocessor is unable to perform; even so a software implementation of a neural network can be made with their advantages and disadvantages.

The Hopfield network demonstrates how the mathematical simplification of a neuron can allow the analysis of the behaviour of large scale neural networks. By characterizing mathematically the effect of changes to the activation of individual units on a property of the entire neural architecture called energy, Hopfield provided the important link between local interactions and global behaviour.

Advantages:
- A neural network can perform tasks that a linear program can not.
- When an element of the neural network fails, it can continue without any problem by their parallel nature.
- A neural network learns and does not need to be reprogrammed.

Disadvantages:
- It can be implemented in any application.
- It can be implemented without any problem.
- The neural network needs training to operate.
- The architecture of a neural network is different from the architecture of microprocessors therefore needs to be emulated.
- Requires high processing time for large neural networks.

Another aspect of the artificial neural networks is that there are different architectures, which consequently requires different types of algorithms, but despite to be an apparently complex system, a neural network is relatively simple.

5.1 Hopfield network

The importance of the different Hopfield networks in practical application is limited due to theoretical limitations of the network structure but, in certain situations, they may form interesting models. This type of ANN is very often used for communication systems. That is the reason, why I chose it for problem solution too. The Neural Networks package supports two types of Hopfield networks, a continuous-time version and a discrete-time version. Both network types have a matrix of weights \( W \) defined as
\[ W = \frac{1}{n} \sum_{i=1}^{D} \xi_i^T \xi_i \]  
(20)

where: \( D \)...is the number of class patterns (\( \xi_1, \xi_2, ..., \xi_D \)) vectors consisting of +/-1 elements, to be stored in the network, and \( n \) is the number of components, the dimension, of the class pattern vectors.

Discrete-time Hopfield networks have the following dynamics:
\[ x(t+1) = \text{Sign}(Wx(t)) \]  
(21)

In this equation is applied to one state, \( x(t) \), at a time. At each iteration the state to be updated is chosen randomly. This asynchronous update process is necessary for the network to converge, which means that \( x(t) = \text{Sign}(Wx(t)) \).

A distorted pattern, \( x(0) \), is used as initial state for this system and the associated pattern is the state toward which the difference equation converges. That is, starting with \( x(0) \) and then iterating. It gives the associated pattern when the equation converged.

For a discrete-time Hopfield network, the energy of a certain vector \( x \) is given by
\[ E(x) = -xW_x^T \]  
(22)

It can be shown that, given an initial state vector \( x(0), x(t) \) in Eq. (20) will converge to a value having minimum energy. Therefore, the minima of Eq. (21) constitute possible convergence points of the Hopfield network.
network and, ideally, these minima are identical to the class patterns \( \{\xi_1, \xi_2, \ldots, \xi_D\} \). Hence, one can guarantee that the Hopfield network will converge to some pattern, but one cannot guarantee that it will converge to the right pattern.

Note that the energy function can take negative values; this is, however, just a matter of scaling. Adding a sufficiently large constant to the energy expression it can be made positive.

The continuous Hopfield network is described by the following differential equation

\[
\frac{dx(t)}{dt} = -x(t) + W_\sigma \big[x(t)\big]
\]

(23)

where \( x(t) \) is the state vector of the network, \( W_\sigma \) represents the parametric weights, \( \sigma \) is a nonlinearity acting on the states \( x(t) \).

This equation is solved using an Euler simulation.

To define a continuous-time Hopfield network, you have to choose the nonlinear function \( \sigma \). There are two choices supported by the package, SaturatedLinear and the default nonlinearity of Tanh.

For a continuous-time Hopfield network, defined by the parameters can define the energy of a particular state vector \( x \) as

\[
E(x) = -\frac{1}{2} x W_x^T + \sum_{i=1}^{m} [\sigma^{-1}(t) dt]
\]

(24)

As for the discrete-time network, it can be shown that given an initial state vector \( x(0) \), the state vector \( x(t) \) in (23) converges to a local energy minimum. Hence, the minima of (24) constitute the possible convergence points of the Hopfield network and ideally these minima are identical to the class patterns \( \{\xi_1, \xi_2, \ldots, \xi_D\} \). However, there is no guarantee that the minima will coincide with this set of class patterns.

5 Conclusion

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.

The noises which are the basic problem for signal transmission are calculating and optimizing with MATLAB programme too.

Another possibility is to implement all inputs parameters into artificial neural networks (ANN). ANN is very goof application for analysis and optimization of communication systems with lots of inputs parameters and different conditions which work upon the system.

References:


