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Modeling weather-resilient laser communication: PPM performance with SNSPD in satellite links

V.E. Merzlinkin[1,2]✉, A.V. Khmelev[1,2,4,5], D.O. Sevryukov[1,3], R.M. Bakhshaliev[1,3], S.D. Levashov[1,3], V.L. Kurochkin[1,2,4]

[1] QSpace Technologies LLC, Moscow, Russia;

[2] National University of Science and Technology MISiS, Moscow, Russia;

[3] National Research University Higher School of Economics, Moscow, Russia;

[4] Moscow Institute of Physics and Technology, Dolgoprudny, Russia;

[5] Russian Quantum Center, Skolkovo, Russia

✉ v.merzlinkin@goqrate.com

Abstract. Laser communication using satellites represents a promising avenue for data transmission in geographically distant areas without advanced infrastructure. This approach is characterized by its high transmission rate and low power requirements, providing substantial benefits over optical fiber and radio communication. However, the optical channel should exhibit greater transparency for light transmission, resulting in a severely restricted application of this technique for information transmission during adverse weather conditions or over long distances. To mitigate the limitations, the employment of a superconducting single-photon detector as a receiver has been proposed. Here, we provide a numerical analysis of a laser communication system to determine the atmospheric attenuation thresholds required to establish a reliable laser link using the pulse position modulation (PPM) scheme and superconducting nanowire single-photon detectors (SNSPD).

Keywords: laser communication, satellite, SNSPD, PPM

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Моделирование устойчивой к атмосферным воздействиям лазерной связи: характеристики PPM с SNSPD в спутниковых линиях связи

В.Е. Мерзлинкин[1,2]✉, А.В. Хмелев[1,2,4,5], Д.О. Севрюков[1,3],
Р.М. Бахшалиев[1,3], С.Д. Левашов[1,3], В.Л. Курочкин[1,2,4]

[1] ООО «КуСпэйс Технологии», Москва, Россия;

[2] Национальный исследовательский технологический университет «МИСИС», Москва, Россия;

[3] Московский физико-технический институт (национальный исследовательский университет), г. Долгопрудный, Россия;

[4] Национальный исследовательский университет «Высшая школа экономики», Москва, Россия;

[5] Российский квантовый центр, Сколково, Россия

✉ v.merzlinkin@goqrate.com

Аннотация. Лазерная связь со спутником является перспективным методом передачи данных в географически удаленных регионах с недостаточно развитой инфраструктурой. Данная технология обладает высокой скоростью передачи информации и низким энергопотреблением, что обеспечивает ее существенные преимущества перед традиционными способами связи. Однако критически важным требованием к оптическому каналу является высокая прозрачность для эффективного распространения светового сигнала, что накладывает значительные ограничения на применение данного метода в условиях неблагоприятных метеорологических явлений или на значительных расстояниях. Для снижения указанных ограничений предложено использование сверхпроводникового однофотонного детектора (СПОД) в качестве приемного устройства. В ходе численного моделирования лазерной системы связи были определены пороговые значения атмосферного ослабления, при которых обеспечивается надежная установка соединения при применении схемы фазово-импульсной модуляции (PPM) в сочетании со СПОД.

Ключевые слова: лазерная связь, спутник, сверхпроводниковый однофотонный детектор, PPM

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Introduction

Laser communication between low Earth orbit satellites and ground stations represents a promising advancement in data transmission technologies [1]. While offering notable advantages in data rate and energy efficiency, this method faces inherent limitations that prevent its widespread adoption for long-distance communication. However, the use of superconducting detectors, characterized by minimal dead time, high quantum efficiency, and low dark count rates, enables the detection of signals significantly attenuated by atmospheric absorption, scattering, and adverse weather conditions [2–5].

Given that these detectors exhibit low timing jitter and sharp signal rise times, PPM proves to be the most efficient encoding scheme. According to the PPM scheme, information is encoded by the temporal position of a pulse within a predefined time slot, allowing the transmission of multiple bits per symbol [6]. We conduct a theoretical study of laser beam attenuation under clear atmospheric circumstances and signal-to-noise dependence, and we calculate the threshold for extra losses that might compensate for adverse weather impacts in order to achieve reliable laser communication in this system.

Methods and Results

One of the key parameters in modeling optical laser communication is signal attenuation ($\boldsymbol{C}_{att}$), which for a satellite-to-ground link depends on the spacecraft's orbital parameters:

$$C_{att} = C_{dif}\left(h, w_0, \lambda, \theta_{El}\right) \cdot C_{pointing}\left(\theta_{err}\right) \cdot C_{weather}\left(\kappa\right) \cdot C_{turb}\left(\theta_{El}, \lambda\right) \cdot C_{ref}\left(\theta_{El}\right), \tag{1}$$

where C_{dif} is the the attenuation due to optical beam diffraction, $C_{pointing}$ is the losses from spacecraft pointing errors toward the ground station, C_{turb} is the atmospheric turbulence-induced attenuation, $C_{weather}$ is the the atmospheric attenuation coefficient, h is the the spacecraft's orbital altitude, λ is the the laser wavelength, $\boldsymbol{\theta}_{El}$ is the the spacecraft's elevation angle above the ground station, w_0 is the the output aperture radius (beam waist) of the spacecraft's optical system, $\boldsymbol{\theta}_{err}$ is the pointing error of the spacecraft relative to the ground station, κ is the the atmospheric extinction coefficient.

The optical link budget between laser terminal Vector and a ground station employing a 600 mm aperture receiver was computationally analyzed (see Fig. 1).

The aforementioned dependencies of signal attenuation in the satellite-to-ground communication channel and the background noise level enable determination of the signal-to-noise ratio during optical signal detection at the ground station using SNSPD. It also allows us to estimate the bit error rate (BER) for the PPM scheme [6] with the number of time slots (L = 4) as

$$\mathrm{BER}_{\mathrm{PPM}} = \frac{1}{2}\,\mathrm{erfc}\left(\frac{1}{2\sqrt{2}}\sqrt{SNR\frac{L}{2}\log_2 L}\right). \tag{2}$$

Numerical simulations were performed to evaluate the potential enhancement of the link budget through implementation of a superconducting nanowire single-photon detector as the receiver

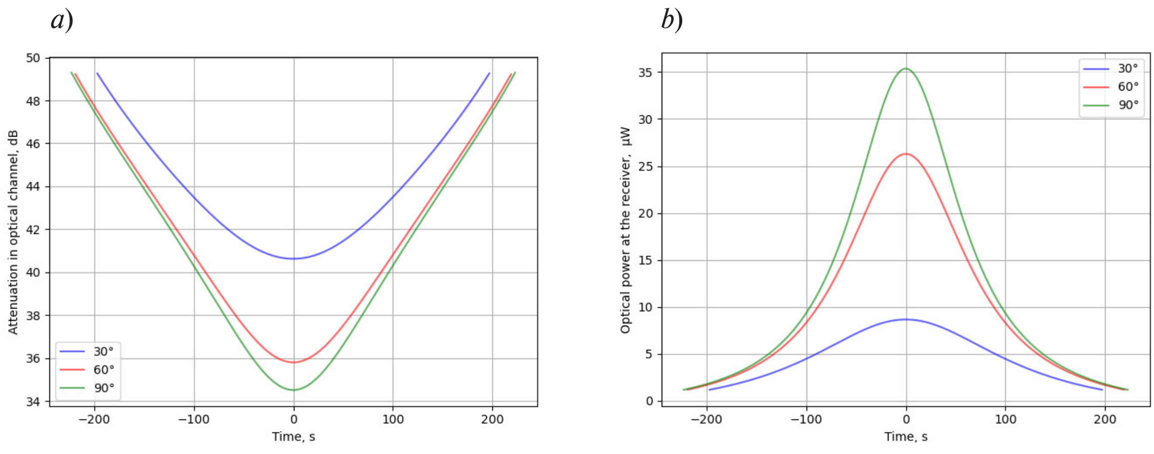

Fig. 1. Optical attenuation of a laser link (*a*). Optical power at the receiver according to the characteristics of laser terminal Vector [7, 8] and Eq. 1 (*b*)

(see Fig. 2). The minimum optical power was calculated based on two target bit error rate values: BER = 10^{-3}, selected as the threshold at which error-correcting codes (such as LDPC) enable error-free communication, and BER = 10^{-12}, chosen to ensure a 0.01% probability of a single error occurring per satellite communication session. The noise signal was normalized such that one data transmission period (3.125 MHz) corresponded to 1 and 0.5 noise photons, respectively, for the two BER cases under consideration.

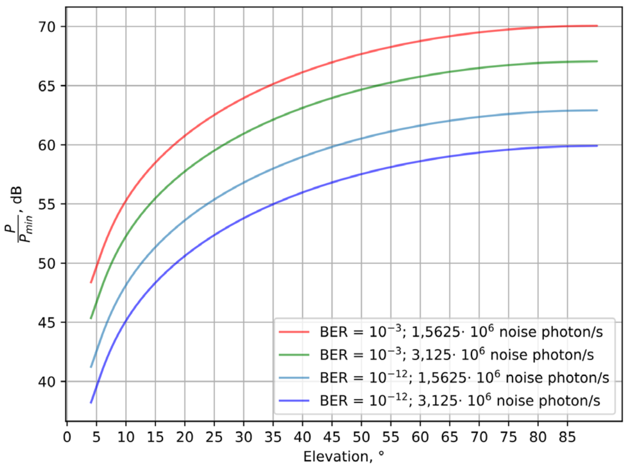

Fig. 2. Atmospheric attenuation thresholds with different BER and noise rate for laser terminal Vector

Conclusion

We have demonstrated that an SNSPD-based laser communication system employing PPM can tolerate additional losses up to 70 dB while maintaining a BER of 10^{-3} at 0,5 noise photons per period, and 60 dB at an ultra-low BER of 10^{-12} with 1 noise photons per period (θ_{El} = 90°). These loss budgets have confirmed that the system is capable to maintain stable satellite links through moderate atmospheric obscuration.

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THE AUTHORS

MERZLINKIN Vitalii E.
v.merzlinkin@goqrate.com
ORCID: 0000-0002-4310-2619

SEVRYUKOV Dmitry O.
d.sevryukov@goqrate.com
ORCID: 0009-0000-8253-7263

LEVASHOV Sergey D.
sergey.d.levashov@gmail.com
ORCID: 0009-0006-4080-0442

KHMELEV Aleksandr V.
a.khmelev@goqrate.com
ORCID: 0000-0003-1511-1128

BAKHSHALIEV Ruslan M.
r.bakhshaliev@goqrate.com
ORCID: 0009-0006-5851-6175

KUROCHKIN Vladimir L.
v.kurochkin@rqc.ru
ORCID: 0000-0002-1599-9801

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