# Probability of Erroneous Data Registration in a Single Photon Erasure-Type Communication Channel with a Receiver Based on a Photon Counter

**A.M. Timofeev**

*Belarusian State University of Informatics and Radioelectronics, Brovki str., 6, Minsk 220013, Belarus*

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**Abstract**

When measuring low-power optical signals, it is necessary to ensure the highest reliability of the received data, which is especially important for single-photon communication channels. This determines the expediency of using photon counters as receiving modules for such channels. They are highly sensitive, but are characterized by data recording errors. Therefore, the purpose of this work was to investigate the influence of the intensity of the registered optical radiation $J_0$ during the transmission of binary symbols “0” on the probability of registering symbols “1” at the output of the communication channel in the presence of symbols “0” at its input $P(1/0)$.

The statistical distributions of the mixture of the number of dark and signal pulses at the output of the photon counter during the registration of binary symbols “0” $P_{st0}(N)$ were determined. To do this, a technique was used to reduce information loss. As a result, the minimum probability $P(1/0)$ was reached.

The probabilities $P(1/0)$ were calculated for a communication channel containing a photon counter as a receiving module. This calculation was carried out at different values of the supply voltage of the avalanche photodetector $U$ and the intensity of the optical signal used to transmit the binary symbols “0” $J_0$.

The experimental results showed that with increasing optical signal intensity $J_0$, the dependences $P(1/0)$ on $J_0$ initially remain almost unchanged and retain a constant value. However, with a further increase in $J_0$, there is a linearly increasing character of the dependences $P(1/0)$ on $J_0$. Moreover, with other equal reception parameters, such a character of the dependences $P(1/0)$ on $J_0$ begins to manifest itself at higher intensities of the optical signal $J_0$ with an increase in the supply voltage of the avalanche photodetector.

**Keywords:** photon counter, single photon communication channel, probability of erroneous registration of binary symbols.

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***Адрес для переписки:***
*Тимофеев А.М.*
*Белорусский государственный университет информатики и радиоэлектроники,*
*ул. П. Бровки, 6, г. Минск 220013, Беларусь*
*e-mail: tamvks@mail.ru*

***Address for correspondence:***
*Timofeev A.M.*
*Belarusian State University of Informatics and Radioelectronics,*
*Brovki str., 6, Minsk, 220013, Belarus*
*e-mail: tamvks@mail.ru*

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# Вероятность ошибочной регистрации данных в однофотонном канале связи стирающего типа с приёмником на основе счётчика фотонов

**А.М. Тимофеев**

*Белорусский государственный университет информатики и радиоэлектроники, ул. П. Бровки, 6, г. Минск 220013, Беларусь*

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При измерении маломощных оптических сигналов, передаваемых в каналах однофотонной связи, приёмные модули должны обеспечивать наибольшую достоверность принятых данных.

В этой связи целесообразно использовать счётчики фотонов, которые являются высокочувствительными, однако характеризуются ошибками регистрации данных. Поэтому цель работы – исследовать влияние интенсивности регистрируемого оптического излучения $J_0$ при передаче двоичных символов «0» на вероятность регистрации на выходе канала связи символов «1» при наличии символов «0» на его входе $P(1/0)$.

На основе методики уменьшения потерь информации определены статистические распределения смеси числа темновых и сигнальных импульсов на выходе счётчика фотонов при регистрации двоичных символов «0» $P_{st0}(N)$, при которых вероятность $P(1/0)$ минимальная.

Определены вероятности $P(1/0)$ для канала связи, содержащего в качестве приёмного модуля счётчик фотонов при различных значениях напряжения питания лавинного фотоприёмника $U_{\text{пит}}$ и интенсивности оптического сигнала, используемого для передачи двоичных символов «0» $J_0$.

Экспериментальные результаты показали, что с увеличением интенсивности оптического сигнала $J_0$ зависимости $P(1/0)$ от $J_0$ вначале практически не изменяются и сохраняют постоянную величину. Однако при дальнейшем увеличении $J_0$ имеет место линейно возрастающий характер зависимостей $P(1/0)$ от $J_0$. Причём при прочих равных параметрах приёма такой характер зависимостей $P(1/0)$ от $J_0$ начинает проявляться при бóльших интенсивностях оптического сигнала $J_0$ с увеличением напряжения питания лавинного фотоприёмника.

**Ключевые слова:** счётчик фотонов, канал однофотонной связи, вероятность ошибочной регистрации двоичных символов.

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***Адрес для переписки:***
*Тимофеев А.М.*
*Белорусский государственный университет информатики и радиоэлектроники,*
*ул. П. Бровки, 6, г. Минск 220013, Беларусь*
*e-mail: tamvks@mail.ru*

***Address for correspondence:***
*Timofeev A.M.*
*Belarusian State University of Informatics and Radioelectronics,*
*Brovki str., 6, Minsk, 220013, Belarus*
*e-mail: tamvks@mail.ru*

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## Introduction

When building modern infocommunication systems, it is necessary to ensure sufficiently high reliability of the technical means used for this [1–7]. This is especially important for systems that solve certain problems in the field of information security, for example, by organizing single photon communication channels [8–21]. In such communication channels, each binary bit (symbol) is transmitted using extremely weak optical radiation with an average number of photons no more than several tens. As a result, it becomes possible to ensure absolute secrecy and confidentiality of the transmitted information through the use of a quantum mechanical resource when encoding the transmitted data.

When implementing single-photon communication channels, a number of rather complex technical problems arise, in particular, the problem of registering such a weak optical radiation. In this regard, it is advisable to use photon counters in such communication channels, which have a sufficiently high sensitivity [22–25]. It should be noted that, due to the imperfection of their characteristics, photon counters can lead to errors in data registration, the causes of which are, in particular, non-zero dead time, quantum registration efficiency different from unity, etc. [24].

Quantum detection efficiency is the ratio of the number of optical radiation photons registered by the photon counter to the total number of photons received [24].

The dead time of the photon counter is the time during which the photon counter is not sensitive to the optical radiation incident on it [24].

Known methods for estimating the probabilities of erroneous data recording for single photon communication channels [5, 7] are not applicable to single photon communication channels with erasure. Such communication channels do not require additional communication lines for transmitting and receiving clock pulses, which distinguishes them favorably from other communication channels. At the same time, they are characterized by the presence of errors of two types, one of which is the registration of characters with different names. A mathematical model for the specified communication channel was built in [25], and in [26], theoretical studies were carried out to estimate the probability of erroneous data recording. However, in the literature there is no assessment of the influence of the intensity of the detected optical radiation during the transmission of information in a single photon communication channel with erasure, which contains a photon counter as a receiving module, on the probability of registering unlike symbols.

The object of study was an asynchronous binary asymmetric homogeneous fiber-optic communication channel without memory and with erasure, containing as a receiving module a photon counter based on an avalanche photodetector FD-115L, connected according to the scheme of passive avalanche suppression. The choice of such a communication channel as the object of study is due to the fact that the fiber optic channel is characterized by the highest bandwidth compared to other data transmission media, for example, metal wires, open space, etc. The passive damping scheme has a lower measurement error of the detected radiation due to the absence of forced avalanche breakdown quenching, which distinguishes it favorably from other schemes – active quenching and pulsed *p*-*n*-junction bias (with gating). Avalanche photodetectors FD-115L are used to operate in the near-IR range and, due to the silicon semiconductor material used in their manufacture, they are characterized by lower noise associated with carrier multiplication and better threshold sensitivity compared to germanium and gallium photodetectors. It should also be noted that silicon avalanche photodetectors make it possible to implement the photon counting mode at room temperatures [24].

The subject of the study was to establish the influence of such parameters of an avalanche photodetector as the intensity of the registered optical radiation and the supply voltage on the probability of registering the symbol “1” at the output of the communication channel in the presence of the symbol “0” at the input of the communication channel.

The purpose of this work was to study the influence of the intensity of the detected optical radiation during the transmission of binary symbols “0” on the probability of registering opposite symbols in a single photon communication channel containing a photon counter as a receiving module.

## Description of the procedure for conducting experimental studies

Further reasoning will be based on the fact that the communication channel is created on the basis of transceivers [27]. The mathematical model of this communication channel was built in [25].

To estimate the probability of registering the symbol "1" at the output of the communication channel in the presence of the symbol "0" at its input, we use the formula [25]:

$$P(1/0) = 1 - \sum_{N=0}^{N_2} P_{st0}(N), \quad (1)$$

where $N_2$ is the upper threshold level of registration, $P_{st0}(N)$ is the statistical distribution of the mixture of the number of dark and signal pulses at the output of the photon counter during the registration of binary symbols "0".

The upper threshold level of registration is the largest number of pulses registered at the output of the photon counter, at which it is concluded that the symbol "0" has been transmitted. When the registered pulses exceed the number $N_2$, it is concluded that the symbol "1" has been transmitted [25, 27].

Dark and signal pulses are pulses that appear at the output of the photon counter, respectively, in the absence of an optical signal and as a result of the action of photons of the detected radiation [24].

Using the setup [27], I obtained the statistical distributions of the mixture of the number of dark and signal pulses at the output of the photon counter when registering binary symbols "0" $P_{st0}(N)$. To achieve the least loss of information in the studied communication channel, the technique [27] was used, on the basis of which the lower and upper threshold levels of registration were chosen, as well as the statistical distributions of the mixture of the number of dark and signal pulses at the output of the photon counter when registering binary symbols "0" $P_{st0}(N)$.

The lower threshold level of registration is the smallest number of pulses registered at the output of the photon counter, at which it is concluded that the symbol "0" has been transmitted. When registering pulses in an amount less than $N_1$, a decision is made that the symbol is absent [25, 27].

The parameter [27] was used as a criterion for the implementation of the applied technique:

$$K_P = \frac{1 - \sum_{N=N_1}^{N_2} P_{st0}(N) + \sum_{N=0}^{N_2} P_{st1}(N)}{1 + \sum_{N=N_1}^{N_2} P_{st0}(N) - \sum_{N=0}^{N_2} P_{st1}(N)}. \quad (2)$$

where $N_1$ is the lower threshold level of registration, $P_{st1}(N)$ is the statistical distribution of the mixture of the number of dark and signal pulses at the output of the photon counter during the registration of binary symbols "1".

It is also important to note that during the research, both the symbols "0" and the symbols "1" were applied to the input of the experimental setup due to the following features of the studied communication channel. The intensity of optical radiation used to transmit a given binary symbol affects not only the probability of erroneous registration of the symbol of the same name, but also the probability of erroneous registration of another binary symbol [25]. Thus, the intensity $J_0$ affects not only the probability of erro-neous registration of the symbol "0", but also the probability of erroneous registration of the symbol "1", and the intensity $J_1$ affects not only the probability of erroneous registration of the symbol "1", but also the probability of erroneous registration of the symbol "0". Given this, as well as the fact that for the considered communication channel, the information transfer rate is maximum with the equiprobable occurrence of binary symbols "0" and "1" at the input of the communication channel [25, 28], the number of binary symbols "0" supplied to the input of the experimental setup, it is advisable to choose equal to the number of binary characters "1". Thus, the condition was fulfilled:

$$P_s(0) = P_s(1) = 0.5, \quad (3)$$

where $P_s(0)$ and $P_s(1)$ are the probabilities of occurrence of symbols "0" and "1", respectively, at the input of the communication channel.

The calculation of the probability $P(1/0)$ was performed for a communication channel containing a photon counter as a receiving module for various values of the supply voltage of the avalanche photodetector $U$ and the intensity of the optical signal used to transmit binary symbols "0" $J_0$.

## Experimental results and their discussion

Figure 1 shows the dependence of the probability of registering the symbol "1" at the output of the communication channel in the presence of the symbol "0" at the input of the communication channel on the intensity of the registered optical radiation used to transmit these symbols.

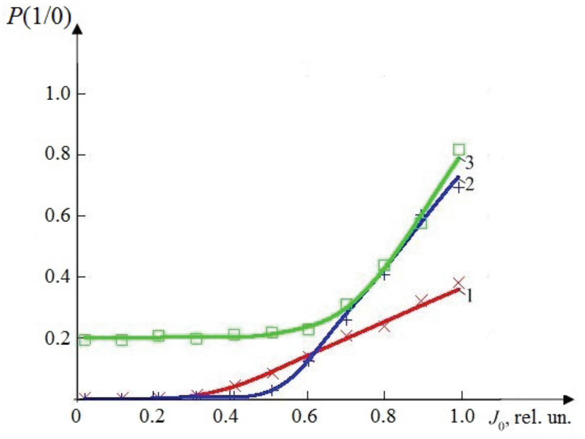


**Figure** – Dependence of the probability of registering the symbol “1” at the output of the communication channel in the presence of the symbol “0” at the input of the communication channel on the intensity of the optical signal used to transmit these symbols; supply voltage of the FD-115L avalanche photodetector: 1 – 52.48 V; 2 – 52.54 V; 3 – 52.65 V

Note that to implement the photon counting mode, the supply voltages of the avalanche photodetector were chosen near the voltage of its avalanche breakdown, which was determined by the method [29] and amounted to 52.71 V. The intensities of optical radiation $J_0$ used to transmit binary symbols “0” are normalized to the maximum value from the studied range. All studies were carried out at a temperature of 293 K.

From the results presented in Figure, it can be seen that each of the dependences $P(1/0)$ on $J_0$ has similar trends for all studied supply voltages of the avalanche photodetector. As the intensity of the optical signal $J_0$ increases, the dependences $P(1/0)$ on $J_0$ initially remain virtually unchanged and remain constant. In this section, the probabilities $P(1/0)$ are approximately equal to the lowest values obtained for the corresponding supply voltages of the avalanche photodetector. With a further increase in $J_0$, a linearly increasing character of the dependences of $P(1/0)$ on $J_0$ is observed.

The indicated character of the change in the dependences $P(1/0)$ on $J_0$ with increasing $J_0$ agrees quite well with the results of mathematical modeling of the considered communication channel, performed in [25] when studying the dependences $P(1/0)$ on $n_{s0}$, where $n_{s0}$ is the average counting rate signal pulses at the output of the photon counter when transmitting the symbols “0”.

Note that the count rate of signal pulses during the transmission of “0” symbols is defined as the number of pulses generated at the output of the receiving module per unit time when exposed to radiation photons corresponding to the registered binary symbols “0” [21, 24]. To estimate the count rate of signal pulses during the transmission of symbols “0”, its average value $n_{s0}$ is used [21, 24].

The presence of segments of dependences $P(1/0)$ on $J_0$ with constant values is explained as follows. At low optical signal intensities $J_0$, the average count rate of signal pulses at the output of the photon counter during the transmission of symbols “0” $n_{s0}$ is small. Therefore, the probability of registration at the output of the counter of photons of pulses in an amount exceeding the upper threshold level of registration $N_2$ is also small. As a result, the probabilities of registering the symbol “1” at the output of the communication channel in the presence of the symbol “0” at the input of the communication channel $P(1/0)$ are equal to the smallest values obtained for the corresponding supply voltages of the avalanche photodetector. With an increase in the intensity of the optical signal $J_0$, the probability of registering pulse photons at the output of the counter in the range from the lower threshold level of registration $N_1$ to the upper threshold level of registration $N_2$ increases. At the same time, the probability of registration at the output of the counter of photons of pulses in an amount exceeding the upper threshold level of registration $N_2$ remains rather low. Thus, the probabilities of registering the symbol “1” at the output of the communication channel in the presence of the symbol “0” at the input of the communication channel $P(1/0)$ are also equal to the smallest values obtained for the corresponding supply voltages of the avalanche photodetector. Therefore, in these $J_0$ ranges, the probabilities $P(1/0)$ remain the least constant (see Figure).

A further increase in the intensity $J_0$ with other equal reception parameters leads to an increase in the probability of registration at the output of the counter of photons of pulses in an amount exceeding the upper threshold level of registration $N_2$. Therefore, the probabilities $P(1/0)$ increase (see Figure). Moreover, with other equal reception parameters, the linearly increasing nature of the dependences $P(1/0)$ on $J_0$, which was determined by the 5 % excess of the probability $P(1/0)$ from the smallest value of the corresponding dependences, begins to manifest itself at higher intensities of the optical signal $J_0$ with increasing supply voltage of the avalanche photodetector:

at $J_0 \geq 1.88 \times 10^{-2}$ rel. units for $U = 52.48$ V;

at $J_0 \geq 2.25 \times 10^{-2}$ rel. units for $U = 52.54$ V;

at $J_0 \geq 49.33 \times 10^{-2}$ rel. units for $U = 52.65$ V.

This is explained as follows. With an increase in the supply voltage of the avalanche photodetector, the smallest value of the criterion $K_P$, which was used in the research, is provided at higher values of the lower threshold level of registration $N_1$. Therefore, with other receiving parameters being equal, the shift in the statistical distributions of the mixture of the number of dark and signal pulses during the transmission of symbols "0" $P_{st0}(N)$, which results in an increase in the probability $P(1/0)$ [25–27], occurs at higher intensities of the optical signal $J_0$ with an increase in the supply voltage of the avalanche photodetector.

It is also seen from the presented results that at sufficiently large values of $U$, the probability $P(1/0)$, corresponding to the section of the dependence of $P(1/0)$ on $J_0$ with constant values, turns out to be higher than at lower supply voltages of the avalanche photodetector (see Figure). For example, the probabilities $P(1/0)$ corresponding to $J_0 = 21.23 \times 10^{-2}$ rel. units, are respectively:

$0.20 \times 10^{-2}$ at $U = 52.48$ V and $20.89 \times 10^{-2}$ at $U = 52.65$ V.

This is due to the fact that at low values of the supply voltage of the avalanche photodetector, the dark pulse count rate is low [24], so the probability $P(1/0)$ does not reach large values and is close to zero.

It is important to note that the dark pulse count rate is defined as the number of pulses generated at the output of the receiving module per unit time when there is no detected optical radiation. The greater the number of dark pulses will be formed per unit time, the greater the probability that the symbol "0" and the symbol "1" will be received, respectively, in the absence of the binary symbol "0" and its presence at the input of the communication channel [25–27].

As the supply voltage of the avalanche photodetector increases, the dark pulse count rate nt increases [24]. This leads to the fact that even at the lowest of the studied optical signal intensities $J_0$, the probability $P(1/0)$ is very high (see Figure).

## Conclusion

As applied to an asynchronous binary asymmetric homogeneous fiber optic communication channel without memory and with erasure, containing as a receiving module a photon counter based on an avalanche photodetector FD-115L with switching on according to the passive avalanche suppression scheme. The probability of registering the symbol "1" at the output of the communication channel in the presence of the symbol "0" at its input $P(1/0)$ is made.

Based on the information loss reduction technique, the statistical distributions of the mixture of the number of dark and signal pulses at the output of the photon counter during the registration of binary symbols "0" $P_{st0}(N)$ are determined, at which the probability $P(1/0)$ is minimal.

The dependences of the probability $P(1/0)$ on the intensity of the optical signal $J_0$ used to transmit binary symbols "0" are established. It is found that, as the intensity of the optical signal $J_0$ increases, the dependences $P(1/0)$ on $J_0$ initially remain almost unchanged and retain a constant value. However, with a further increase in $J_0$, there is a linearly increasing character of the dependences $P(1/0)$ on $J_0$. Moreover, with other equal reception parameters, such a character of the dependences $P(1/0)$ on $J_0$ begins to manifest itself at higher intensities of the optical signal $J_0$ with an increase in the supply voltage of the avalanche photodetector.

The performed experimental results showed that in order to reduce the probability of registering the symbol "1" at the output of the communication channel in the presence of the symbol "0" at its input $P(1/0)$, it is important to select not only the intensity of the used optical radiation $J_0$, but also the supply voltage of the avalanche photodetector $U$. This makes it possible to achieve minimal information loss in the studied communication channel.

The results obtained in this work can be used to create quantum cryptographic asynchronous communication systems containing photon counters with extended dead time as receiving modules and characterized by high reliability of received data.

The author of this work considers research aimed at substantiating the choice of an avalanche photodetector used in the construction of a photon counter to be very topical. Such photodetectors can differ both in the structure of the semiconductor regions and in the area of the photosensitive surface. In this regard, in the course of further comprehensive studies, it is

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planned to determine how these parameters affect the probability of erroneous registration of binary data in relation to an asynchronous binary asymmetric homogeneous single-photon communication channel without memory and with erasure.

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