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Evaluation of noise immunity of multispectral optoelectronic message transmission systems

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Abstract. The paper considers an approach to evaluate the noise immunity of multispectral optoelectronic systems for transmitting information messages. The relevance of this work is determined by the need to increase the reliability of optical communication, identification, navigation, and control channels under background illumination, electromagnetic interference, optical disturbances, partial channel obstruction, and nonuniform spectral attenuation of signals. It is shown that a simple increase in the power of a single semiconductor emitter increases the amplitude of the received signal but does not eliminate the fundamental vulnerability of a single-spectral system to selective interference within the chosen wavelength range. It is shown that the real advantage of the multispectral approach is determined not only by the number of spectral channels but also by their statistical independence, differences in the spectral characteristics of interference, and the ability of individual channels to retain information content under difficult transmission conditions. The proposed model can be used for numerical simulation, experimental verification, and optimization of LED-based multispectral message transmission systems for autonomous moving objects, unmanned aerial vehicles, robotic platforms, and local sensor networks.

Keywords: multispectral optoelectronic system, message transmission, noise immunity, signal-to-noise ratio, spectral channels, noise covariance matrix, Mahalanobis distance, error probability, LED emitters, optical wireless communication.

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1. Introduction

Interference-resistant transmission of information messages is one of the key tasks of modern optoelectronic systems for communication, identification, navigation, and control. Optical wireless systems, particularly visible light communication and free-space optical communication, are considered as a promising alternative or complement to conventional radio-frequency channels because of their wide available bandwidth, the possibility of combining illumination and data transmission, low susceptibility to radio-frequency interference, and suitability for local high-speed information exchange [1–3].

Recent reviews confirm the active development of Visible Light / Optical Wireless communication (VLC/OWC) technologies, particularly in high-speed transmitters and receivers, digital modulation methods, integration of communication with lighting and sensing, and the use of intelligent reflecting surfaces to improve optical channel quality [3, 4]. One promising direction to improve the noise immunity of optoelectronic message transmission systems is the multispectral approach. Its essence is that an information message is transmitted not through a single channel but through several spectrally separated optical channels. These channels may correspond to individual visible spectral bands in the near-infrared range, or combinations of several LED and micro-LED sources. The practical feasibility of this approach is supported by recent works on WDM-OWC (Wavelength Division Multiplexing Optical Wireless Communication) and WDM-VLC (Wavelength Division Multiplexing Visible Light Communication), where the use of several wavelengths is considered as a means of increasing throughput, channel separation, and robustness of optical transmission [5–7].

Modern semiconductor emitters in the visible and near-infrared ranges are characterized by sufficiently high optical power [8, 9], energy efficiency, high speed, and the possibility of direct electronic modulation. This makes it possible to use them not only as illumination or indication sources but also as transmitting elements of optoelectronic systems for information message transmission. The simplest way to increase the range or reliability of reception in such a system is to increase the power of a single emitter. In this case, the amplitude of the received signal increases and, under certain conditions, the signal-to-noise ratio also increases.

However, a simple increase in the power of a single channel does not remove the fundamental limitation of a single-spectral system. Such a system remains sensitive to all disturbances that affect the selected spectral range: background illumination, solar glare, spectrally close artificial light sources, partial obstruction of the optical path, and attenuation of radiation by fog, dust, smoke, or precipitation. If only the spectral channel is significantly suppressed, increasing its power does not always provide sufficient recovery of reception reliability, especially in the presence of selective interference or limitations on the permissible optical power.

In contrast, a multispectral system forms a multi-dimensional space of spectral features. In such a system, the receiver analyzes not only the total signal amplitude but also the energy distribution among individual spectral channels. In other words, a message can be recognized not only by its intensity level but also by the spectral "profile" of the signal. This increases the probability of correct message reception under background illumination, fog, dust, smoke, precipitation, partial obstruction of the optical channel, or selective optical interference.

The use of several spectral channels creates additional information redundancy: if one channel is partially attenuated or noisy, other channels may retain sufficient information content for signal detection and message decoding. Therefore, the advantage of the multispectral approach lies not only in a possible increase in the total signal-to-noise ratio but also in improving the system robustness to nonuniform spectral attenuation and local optical interference. Studies of MIMO-VLC (Multiple-Input Multiple-Output Visible Light Communication) also show that spatial and spectral channel separation is an important means of improving the robustness of optical wireless systems [10].

At the same time, the effectiveness of the multispectral approach is not determined only by the number of spectral channels. If the noise in different channels is statistically independent or weakly correlated, channel combining increases the total signal-to-noise ratio and reduces the probability of message reception error. If the channels contain a common noise component, for example, due to background illumination, electronic coupling, a common photodetection path, or digital signal processing, the real gain from multispectral operation may be substantially smaller. Therefore, a correct assessment of noise immunity must consider not only the individual signal and noise levels in each channel but also the interchannel noise correlation.

This problem is especially important for autonomous moving objects, unmanned aerial vehicles, robotic platforms, transport systems, and local sensor networks that must operate under limited availability of the radio-frequency spectrum, intense electromagnetic interference, or increased requirements for locality and directivity of the transmitting channel [11–14].

This paper aims to develop a generalized model for evaluating the noise immunity of a multispectral optoelectronic message transmission system with an arbitrary number of spectral channels. The main attention is paid to calculating the signal-to-noise ratio, accounting for the noise covariance matrix, determining the possible gain from optimal channel combining, and estimating the probability of message reception error. The proposed approach allows us to quantitatively determine the conditions under which a multispectral system has a practical advantage over a single-spectral configuration or a simple increase in the power of one optical channel.

2. General model of a multispectral optical channel

The photodetector, or a set of photodetectors, converts the received optical power $P_{sig,k}$ of the k-th channel into photocurrent. If R_k is the spectral responsivity of the photodetector in the k-th channel, then the useful electrical component of the signal is

$$s_k = R_k P_{sig,k} \,.$$

Hereafter, s_k is regarded as the amplitude of the useful electrical signal after photodetection and extraction of the information component. It can be expressed either as a photocurrent or as a voltage after a transimpedance amplifier, provided that the noise variance σ_k^2 is referred to the same electrical quantity. Even if the average background level is compensated, it increases shot noise and therefore cannot be completely ignored in the SNR calculation [8].

After determining the useful electrical signal s_k and the total noise variance σ_k^2, the signal-to-noise ratio of a single spectral channel is written as

$$\mathrm{SNR}_k = \frac{s_k^2}{\sigma_k^2} \,.$$

Let the number of channels be M. Then, for the entire M-channel system, we introduce the vector of useful signals

$$\mathbf{s} = [s_1, s_2, \dots, s_M]^{\mathrm{T}}.$$

The observation vector in the problem of optical signal detection can be represented in terms of two hypotheses:

$$H_0 : \mathbf{y} = \mathbf{n} \,,\ H_1 : \mathbf{y} = \mathbf{s} + \mathbf{n} \,,$$

where **y** is the observation vector, and **n** is the vector of noise and interference.

The noise covariance matrix *Σ*, which describes the statistical relationship between noise components in different channels, is defined as

$$\Sigma_{ij} = \begin{cases} \sigma_i^2, & i = j, \\ \rho_{ij}\,\sigma_i\,\sigma_j, & i \neq j. \end{cases}$$

Here, ρ_{ij} is the correlation coefficient between the noise components of the *i*-th and *j*-th spectral channels. For independent noise, $\rho_{ij} = 0$ for $i \neq j$; in this case, *Σ* is effectively a diagonal matrix. In expanded form, it can be written as

$$\Sigma = \begin{bmatrix} \sigma_i^2 & \rho_{12}\sigma_1\sigma_2 & \cdots & \rho_{1M}\sigma_1\sigma_M \\ \rho_{21}\sigma_2\sigma_1 & \sigma_2^2 & \cdots & \rho_{2M}\sigma_2\sigma_M \\ \vdots & \vdots & \ddots & \vdots \\ \rho_{M1}\sigma_M\sigma_1 & \rho_{M2}\sigma_M\sigma_2 & \cdots & \sigma_M^2 \end{bmatrix}.$$

Thus, an *M*-channel optical multispectral message transmission system should be described not as a set of independent scalar signals, but as a vector model in which each spectral channel forms a separate component of the observation vector. This approach allows us to account not only for the useful signal level in each channel but also for the noise structure of the entire system.

The covariance matrix *Σ* is a key element of this model because it simultaneously characterizes the intrinsic noise of each channel and the degree of statistical relationship between noise components in different channels. If the off-diagonal elements of the matrix are zero, the channel noises may be considered independent, and the contribution of each spectral channel to the overall noise immunity of the system is evaluated separately. If the off-diagonal elements are nonzero, this indicates the presence of common noise or interference components, for example, due to background illumination, electronic coupling, a common photodetection path, or digital signal processing.

Therefore, subsequent evaluation of the noise immunity of a multispectral system must consider two limiting cases: independent spectral channels, where the total gain is determined by adding the information content of the individual channels, and correlated channels, where the real gain depends on the structure of the noise covariance matrix. This transition from a scalar description of a single channel to a vector-matrix model of the whole system allows us to correctly evaluate the effectiveness of the multispectral approach, determine the contribution of each channel, and formulate the conditions under which a multichannel configuration provides a real increase in the noise immunity of message transmission.

3. SNR in the absence and presence of noise correlation

If the noise components in the spectral channels are independent, the covariance matrix has the form

$$\Sigma = \operatorname{diag}\left(\sigma_1^2, \sigma_2^2, \ldots, \sigma_M^2\right).$$

In this case, the equivalent output signal-to-noise ratio after optimal channel combining is equal to the sum of the individual signal-to-noise ratios:

$$\mathrm{SNR}_{out} = \sum_{k=1}^{M} \mathrm{SNR}_k = \sum_{k=1}^{M} \frac{s_k^2}{\sigma_k^2}.$$

If all channels are identical and independent, then

$$\mathrm{SNR}_1 = \mathrm{SNR}_2 = \cdots = \mathrm{SNR}_M = \mathrm{SNR}_0$$

and therefore

$$\mathrm{SNR}_{out} = M\mathrm{SNR}_0.$$

Under real conditions, the noise components of different channels may be correlated due to common background illumination, electronic coupling, a common receiving path, or digital processing. Therefore, the simple summation of SNR_k is not always correct. For the general case, we introduce a linear decision statistic

$$z = \mathbf{w}^{\mathrm{T}}\mathbf{y},$$

where **w** is the vector of weighting coefficients. The signal component at the output of the combiner is

$$S_z = \mathbf{w}^{\mathrm{T}}\mathbf{s},$$

and the noise variance at the output is

$$\sigma_z^2 = \mathbf{w}^{\mathrm{T}}\Sigma\mathbf{w}.$$

Thus, the output signal-to-noise ratio is

$$\mathrm{SNR}_z = \frac{(\mathbf{w}^{\mathrm{T}}\mathbf{s})^2}{\mathbf{w}^{\mathrm{T}}\Sigma\mathbf{w}}.$$

Maximization of this generalized ratio with respect to the vector **w** yields the optimal weights

$$\mathbf{w}_{opt} = c\Sigma^{-1}\mathbf{s},$$

where *c* is a nonzero scaling constant. The scaling constant *c* does not affect SNR_z because multiplication of all weights by *c* changes the numerator and denominator in the same way:

$$(c\mathbf{w})^{\mathrm{T}}\mathbf{s} = c\mathbf{w}^{\mathrm{T}}\mathbf{s}, \qquad (c\mathbf{w})^{\mathrm{T}}\Sigma(c\mathbf{w}) = c^2\mathbf{w}^{\mathrm{T}}\Sigma\mathbf{w}.$$

Therefore, the factor c^2 cancels in the ratio SNR_z.

If a channel has a large useful signal s_k, it should receive a larger weight. If a channel has a large noise variance σ_k^2, its weight should be smaller. If the noise of a channel is strongly correlated with the noise of other channels, the receiver must account for this correlation and should not treat this channel as a completely independent source of information.

After substituting the optimal weights, we obtain

$$\mathrm{SNR}_{out} = \mathbf{s}^{\mathrm{T}}\Sigma^{-1}\mathbf{s}.$$

This relation shows that the receiver does not necessarily have to add all channels with equal weights.

A channel with a high useful signal level and low noise may receive a larger weight, while a channel with high noise or strongly correlated interference may receive a smaller weight. In some cases, the weight of an individual channel may even be negative if this helps compensate for a common interference component.

For independent channels, the matrix Σ is diagonal:

$$\Sigma = \mathrm{diag}\left(\sigma_1^2, \sigma_2^2, \ldots, \sigma_M^2\right).$$

Then

$$\Sigma^{-1} = \mathrm{diag}\left(\frac{1}{\sigma_1^2}, \frac{1}{\sigma_2^2}, \ldots, \frac{1}{\sigma_M^2}\right)$$

and the optimal weights become

$$w_k = \frac{s_k}{\sigma_k^2}.$$

Thus, each channel is weighted in proportion to its useful signal and inversely proportional to its noise variance. This corresponds to the intuitive rule that strong and low-noise channels should be weighted more strongly, whereas weak and noisy channels should be weighted less strongly.

4. Quantitative evaluation of signal detection probability

To quantitatively evaluate the separability of the two hypotheses of signal presence (H_1) and signal absence (H_0), it is convenient to use the Mahalanobis distance, which considers not only the difference between mean values but also the covariance structure of the noise [15, 16]:

$$D_M^2 = (\mu_1 - \mu_0)^\mathrm{T} \Sigma^{-1} (\mu_1 - \mu_0).$$

Here, the mean observation vectors are $\mu_0 = \mathbf{0}$ and $\mu_1 = \mathbf{s}$. Accordingly,

$$D_M^2 = \mathbf{s}^\mathrm{T} \Sigma^{-1} \mathbf{s}.$$

Comparing this expression with the optimal output SNR, we obtain

$$D_M^2 = \mathrm{SNR}_{out}.$$

Thus, in this problem, the square of the Mahalanobis distance has a direct physical interpretation as the optimal output signal-to-noise ratio after combining M spectral channels.

For two Gaussian classes with identical covariance matrices and equal a priori probabilities, the probability of discrimination error can be estimated as

$$P_e \approx Q\left(\frac{D_M}{2}\right) = Q\left(\frac{\sqrt{\mathrm{SNR}_{out}}}{2}\right),$$

where Q is the standard Q-function of the normal distribution.

For analytical evaluation, consider the case in which all channels have the same individual SNR_0, and the correlation coefficient between the noise components of any two channels is the same and equal to ρ. The covariance matrix can be written as

$$\Sigma = \sigma^2[(1-\rho) I_M + \rho \mathbf{1}\mathbf{1}^\mathrm{T}],$$

where I_M is the $M \times M$ identity matrix and $\mathbf{1}$ is a vector filled with ones. For the matrix to be positive definite, the following condition must be satisfied:

$$-\frac{1}{M-1} < \rho < 1.$$

If $\mathbf{s} = s_0 \mathbf{1}$. And $\mathrm{SNR}_0 = \frac{s_0^2}{\sigma^2}$, then, after calculation, we obtain $\mathrm{SNR}_{out} = \frac{M}{1+(M-1)\rho}\mathrm{SNR}_0$.

The quantity $\mathrm{M}_{eff} = \frac{M}{1+(M-1)\rho}$ can be interpreted as the effective gain associated with increasing the number of spectral channels. If $\rho = 0$, then $M_{eff} = M$, and the system obtains the maximum gain. If ρ approaches 1, then M_{eff} approaches 1; that is, the M-channel system effectively degenerates into a single channel, because all noise components are fully correlated.

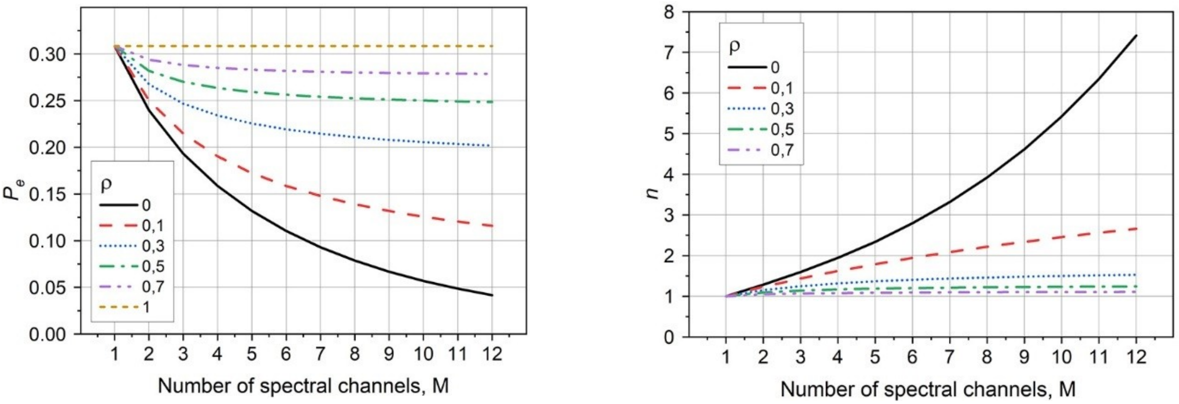
If each spectral channel has $\mathrm{SNR}_0 = 1$, which corresponds to a normalized limiting case in which the useful signal power in each spectral channel is equal to the noise power, then for M channels $\mathrm{SNR}_{out} = M$, $D_M = \sqrt{M}$, and the error probability is determined as

$$P_e \approx Q\left(\frac{\sqrt{M}}{2}\right).$$

For the normalized case $\mathrm{SNR}_0 = 1$, dependences of the discrimination error probability P_e and the noise immunity margin (n, which is calculated as M_{eff}) on the interchannel correlation coefficient ρ were plotted for multispectral systems with the number of channels $M = 2, \ldots 12$. The calculation was performed using the equations given above.

Fig. 1 demonstrates that increasing the number of spectral channels provides a significant reduction in error probability only under weak noise correlation between channels. At $\rho = 0$, the channel noises are independent; therefore, each additional channel increases the total signal-to-noise ratio and reduces P_e. In this case, the multispectral system has the largest gain.

As ρ increases, the interchannel noise components become more similar; that is, the channels contain a common noise component. As a result, the effective number of independent channels decreases, and the gain from multispectral operation gradually decreases. In the limiting case $\rho \to 1$, the noise components of all channels are almost completely correlated; therefore, the M-channel system approaches a single-spectral system in terms of efficiency.



(a) (b)

Fig. 1. Effect of interchannel noise correlation ρ on the efficiency of an *M*-channel multispectral system at $\mathrm{SNR}_0 = 1$: (a) signal discrimination error probability P_e; (b) gain factor of noise immunity compared with a single-spectral system.

Thus, a simple increase in the number of spectral channels does not guarantee a proportional improvement in system characteristics. The practical advantage of the multispectral approach appears when the channels have not only different wavelengths but also statistically weakly correlated noise, different levels of background radiation, and different sensitivity to optical interference and medium attenuation.

5. Conclusions

A generalized model for evaluating the signal-to-noise ratio of a multichannel multispectral optoelectronic message transmission system has been developed. The proposed approach shows that, when the spectral channels are independent, a multispectral system provides an increase in the total signal-to-noise ratio by combining information from several channels. This improves the energy efficiency of reception without simply increasing the power of a single emitter. At the same time, this gain is maximal only when the noise components in the individual spectral channels are statistically independent or weakly correlated.

It has been established that an additional spectral channel is useful not by itself, but only when it contains a sufficient level of useful signal, has an acceptable noise level, and does not duplicate the interference component of other channels. A channel with a weak useful signal, a high background level, or strongly correlated interference may have only a minor practical effect. Therefore, the efficiency of a multichannel system is determined not only by the number of channels but also by the quality of their spectral separation.

It has been shown that the practical advantage of a multispectral system is most fully manifested under difficult operating conditions, such as fog, dust, smoke, precipitation, artificial illumination, solar glare, or local optical interference. Under such conditions, one spectral channel may be partially suppressed or noisy, while other channels may retain sufficient information content for signal detection and reliable message transmission.

It has also been determined that a simple increase in the power of one channel can be effective under idealized conditions when interference is not spectrally selective. However, such a system remains one-dimensional and vulnerable to degradation in the selected spectral range. The multispectral approach, in contrast, provides additional redundancy and increases the probability of preserving information when one of the channels is partially lost or degraded.

The proposed model can be used as a basis for numerical simulation, experimental verification, and optimization of multispectral LED systems for transmitting navigation and identification messages. Practical applications of such systems are promising for autonomous navigation and communication of unmanned aerial vehicles, robotic platforms, transport systems, and other moving objects in environments with limited or unavailable GNSS signals.

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Turukalo A.V.: investigation, software, visualization.

Oliinyk O.S.: investigation, validation, writing – review & editing.

Bystrytskyi H.V.: investigation, visualization, data curation.

Nikolaenko Yu.E.: methodology, validation, writing – review & editing.

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Оцінювання завадостійкості мультиспектральних оптоелектронних системи передачі повідомлень

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Анотація. У статті розглянуто підхід до оцінювання завадостійкості мультиспектральних оптоелектронних систем передавання інформаційних повідомлень. Актуальність роботи зумовлена необхідністю підвищення надійності оптичних каналів зв’язку, ідентифікації, навігації та керування в умовах фонового освітлення, електромагнітних завад, оптичних перешкод, часткового перекриття каналу та нерівномірного спектрального ослаблення сигналів. Установлено, що просте збільшення потужності одного напівпровідникового випромінювача підвищує амплітуду прийнятого сигналу, однак не усуває принципову вразливість односмугової системи до селективних завад у вибраному діапазоні довжин хвиль. Показано, що реальна перевага мультиспектрального підходу визначається не лише кількістю спектральних каналів, а й рівнем їх статистичної незалежності, різницею спектральних характеристик завад і здатністю окремих каналів зберігати інформативність у складних умовах передавання. Запропонована модель може бути використана для числового моделювання, експериментальної верифікації та оптимізації світлодіодних мультиспектральних систем передавання повідомлень для автономних рухомих об’єктів, БПЛА, роботизованих платформ і локальних сенсорних мереж.

Ключові слова: мультиспектральна оптоелектронна система, передавання повідомлень, завадостійкість, відношення сигнал/шум, спектральні канали, коваріаційна матриця шумів, відстань Махаланобіса, ймовірність помилки, світлодіодні випромінювачі, оптичний бездротовий зв’язок.