URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021

Array-Type High-Speed and Large Detection Area Integrated Wireless Optical Receiver

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Abstract

A new high-speed and large detection area integrated wireless optical receiver is proposed. It is composed of a large number of identical optical receivers, each consisting of a high-speed photodiode and a subsequent low-noise amplifier. The output signals of all receivers are combined by an adding circuit so that the signal-to-noise power ratio (SNR) can be improved significantly. Estimates for the achievable data rate as a function of distance between transmitter and receiver are calculated.

1 Introduction

Free-space optical (FSO) communications is already used for a long time. Besides applications like remote control of electronic systems, highly directional free-space infrared communications with high data rates is well established. Commercially available are systems which transmit at data rates up to 1.5 Gbit/s via distances of 1.5 km. In the area of inter-satellite communications a system has been developed transmitting at 5.6 Gbit/s via a distance of 6000 km [1]. The main reason that such systems show such a high performance is that they are highly directional and that they use lenses for beam forming at transmitter and receiver.

On the other hand the performance of free-space optical or infrared indoor communication systems is quite poor. Using white light emitting diodes (LEDs), currently a data rate of 513 Mbit/s for a distance of only 0.3 m could be achieved [2]. Here even an avalanche photodiode with an area of 7 mm^2 and a weakly focusing lens has been used. More recently, in [3] a data rate of 1.3 Gbit/s has been demonstrated, but only via a distance of 0.5 m.

The communication systems discussed so far achieve the described performance only because they use focusing optics. Therefore, they only work if the directions of transmitter and/or receiver are adjusted properly. Such a required adjustment is not acceptable for wireless indoor communication where a user expects that if he switches on a terminal on a desk, the communication is automatically working without any mechanical adjustment.

Instead, in this paper an application scenario is considered where omnidirectional optical or infrared sources at the ceiling of a room are used and the direction of the terminal on a desk need not to be adjusted. The main focus of this paper is the downlink from the infrastructure to a mobile terminal because the downlink usually requires higher data rates than the uplink. For such a scenario, in [4] a non-directional free-space optical transmission system has been presented with a data rate of 50 Mbit/s over a distance of 3 m. The transmitter used 8 laser diodes yielding a total transmit power of 475 mW. A similar experiment with visible light and a data rate of 84 Mbit/s via a distance of 1.4 m has been shown in [5].

The main problem of a non-directional free-space optical transmission system is the small power density (W/m^2) at the receiver. The straight-forward method to cope with this fact is to use photodiodes with large active area. However, they have the disadvantage of a large junction capacitance which leads to a small bandwidth.

This paper presents a solution for this problem: A large number N of small to medium size active area photodiodes is used in parallel so that the total active area is large. Each photodiode is equipped with a subsequent low-noise amplifier. The output signals of all of these optical receivers are summed up so that the signal-to-noise power ratio increases approximately by a factor of N. It is proposed to develop an integrated optoelectronic device consisting of a large number of identical high-speed receivers with an analog electronic circuit summing up the output signals of all receivers [6]. Figure 1 shows a corresponding optoelectronic circuit which uses two levels for summing up signals. In a first step the output signals of each row of receivers are added - in a second step the output signals of the rows are added.

A first study of such a more simple approach was shown in [7] where for an application in a fiber-optical transmission system, the output signals of only four optical receivers were summed up. Furthermore, in [8] a noise analysis of a corresponding multi-photodiode optical wireless receiver with commercial components is given.

2 Range of a Free-space Optical Transmission System

In the following a rough estimate of the achievable bit rate using the array-type optical receiver in an indoor scenario shall be calculated (see Fig.2). It is assumed that a Lambertian radiator is binary modulated by on-off-keying transmitting the average power P_0. The power density at the receiver is:

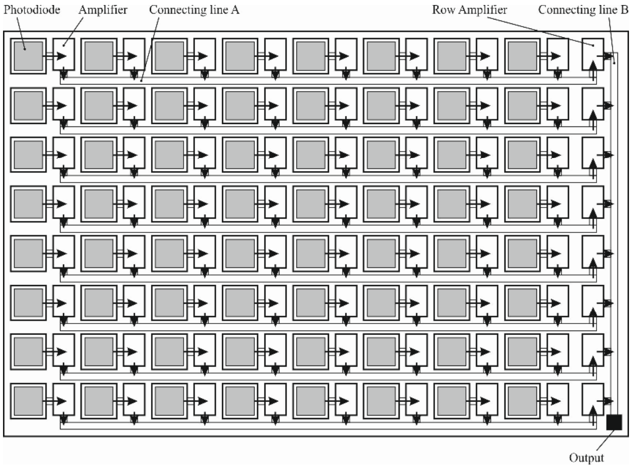

Figure 1. Array-type integrated optical receiver.

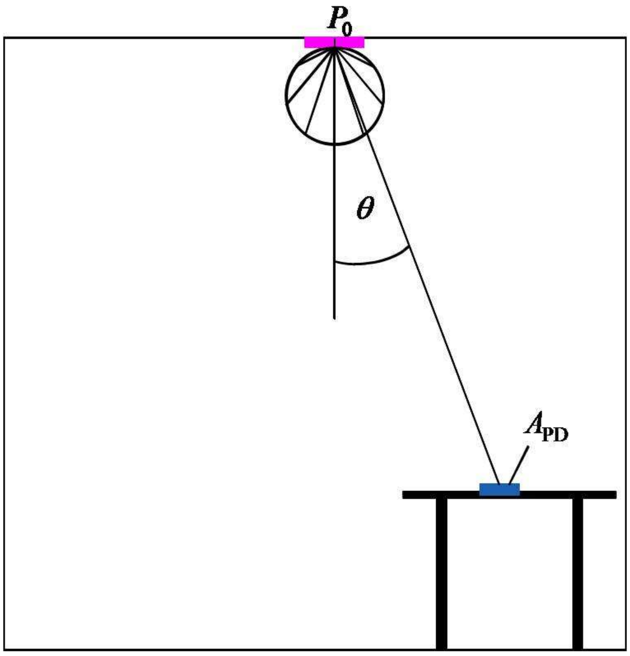

Figure 2. Indoor scenario.

$$P' = P_0 \cdot \frac{1}{\pi\, d^2} \cdot \cos(\theta) \quad (1)$$

where d denotes the distance between transmitter and receiver. The average received power at a single photodiode is:

$$P_r = P_0 \cdot \frac{1}{\pi\, d^2} \cdot \cos^2(\theta) \cdot A_{PD} \quad (2)$$

where A_{PD} denotes the active area of a single photodiode. The average photocurrent $\langle i_{ph} \rangle = I_0$ at a single photodiode is:

$$I_0 = P_0 \cdot \frac{1}{\pi\, d^2} \cdot \cos^2(\theta) \cdot A_{PD} \cdot \frac{e\eta\lambda}{hc} \quad (3)$$

where e is the electron charge, η is the quantum efficiency, λ is the optical wavelength, h is Planck's constant, and c is the velocity of light. For the calculation of the signal-to-noise power ratio (SNR) at the receiver output, the variance of the photocurrent i_{ph} is needed:

$$\sigma_{i_{ph}}^2 = \left\langle \left(i_{ph} - I_0\right)^2 \right\rangle = I_0^2 = \left[\frac{P_0 A_{PD}}{\pi\, d^2} \cdot \cos^2(\theta) \cdot \frac{e\eta\lambda}{hc} \right]^2 . \quad (4)$$

This result is true for on-off-keying.

When combining a PIN photodiode with a low-noise field-effect transistor without matching network, the receiver structure with minimum equivalent input noise is a high-impedance receiver. Neglecting shot noise, the power spectral density (PSD) of its equivalent input noise is given by [9]:

$$S_{i_{eq}}(\omega) = 2kT_0\omega^2 R_s C_s^2 \left[F_{min}(\omega) + \frac{R_n}{R_s} \cdot \frac{(C_s + C_{gs})^2}{C_s^2} \right] . \quad (5)$$

where k denotes Boltzman's constant, T_0 is the temperature, R_s is the series resistance of the photodiode and C_s its junction capacitance, F_{min} is the minimum noise figure of the FET, R_n is the equivalent noise resistance and C_{gs} is the gate-source capacitance.

The PSD of the equivalent input noise $S_{i_{eq}}(\omega)$ increases quadratically with (angular) frequency ω and is mainly determined by the mismatch between photodiode and FET. For low-noise transistors, the minimum noise figure F_{min} can be neglected compared with the second term in the brackets of (5). This simplifies the PSD to the following result:

$$S_{i_{eq}}(\omega) = 2kT_0\omega^2 R_n \cdot (C_s + C_{gs})^2 . \quad (6)$$

The electrical receiver is modeled by a simple low-pass filter. The noise power at its output can be roughly estimated by integrating the PSD $S_{i_{eq}}(\omega)$ versus frequency. As an approximation the cut-off frequency of the low-pass filter is chosen: $\omega_c = 2\pi \cdot \frac{f_{bit}}{2}$, where f_{bit} denotes the bit rate. The variance of the noise finally results to:

$$\sigma_{i_{eq}}^2 = \frac{1}{2\pi} \int_{-\pi f_{bit}}^{\pi f_{bit}} S_{i_{eq}}(\omega) = \frac{2\pi^2}{3} kT_0 R_n \cdot (C_s + C_{gs})^2 f_{bit}^3 . \quad (7)$$

The SNR for a single receiver finally results to:

$$\frac{\sigma_{i_{\mathrm{ph}}}^2}{\sigma_{i_{\mathrm{eq}}}^2} = \frac{\left[\dfrac{P_0 A_{\mathrm{PD}}}{\pi\, d^2} \cdot \cos^2(\theta) \cdot \dfrac{e\eta\lambda}{hc}\right]^2}{\dfrac{2\pi^2}{3} k T_0 R_{\mathrm{n}} \cdot (C_{\mathrm{s}} + C_{\mathrm{gs}})^2 f_{\mathrm{bit}}^3} . \qquad (8)$$

The SNR of the array-type receiver containing N photodiode-amplifier combinations yields a value which is by a factor of N larger than that of a single photodiode-amplifier combination. The reason is the following: By summing up N output signals the signal power increases by a factor of N^2 whereas the noise power increases only by a factor of N. Solving for the bit rate gives the final result:

$$f_{\mathrm{bit}} = \sqrt[3]{\frac{\left[\dfrac{P_0 A_{\mathrm{PD}}}{\pi\, d^2} \cdot \cos^2(\theta) \cdot \dfrac{e\eta\lambda}{hc}\right]^2 \cdot N}{\dfrac{2\pi^2}{3} k T_0 R_{\mathrm{n}} \cdot (C_{\mathrm{s}} + C_{\mathrm{gs}})^2 \dfrac{\sigma_{i_{\mathrm{ph}}}^2}{\sigma_{i_{\mathrm{eq}}}^2}}} . \qquad (9)$$

An evaluation of equation (9) for typical parameters of discrete photodiodes and FETs is plotted in Fig. 3. It is assumed that an SNR of 10 dB is sufficient for binary signalling.

Clearly, the above calculation is only a rough estimate for the achievable data rate. Real systems can be further improved using optimized modulation methods, like multicarrier transmission with bit loading and techniques using multiple transmitter and multiple receiver concepts (MIMO) [3].

3 Summary

The concept of a new high-speed large area optical receiver has been presented. It consists of a large number of small to medium size photodiodes and subsequent amplifiers. The output signals of all receivers are added to maximize the SNR at the output. The achievable range for an indoor free-space communication system has been estimated.

7 References

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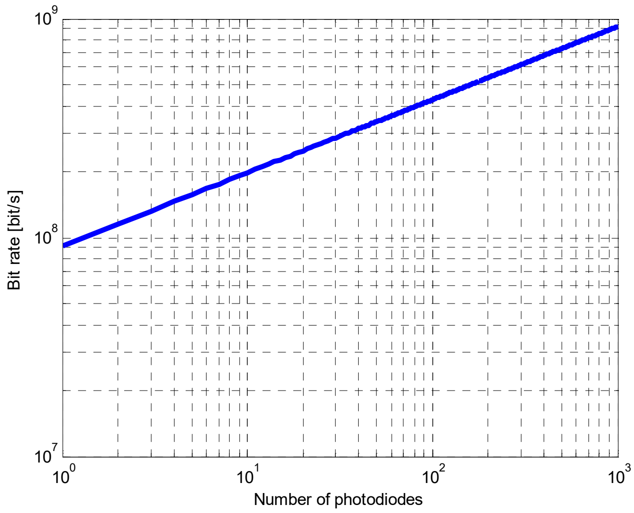

Figure 3. Range of a free-space optical link. Parameters: $P_0 = 100$ mW, $A_{\mathrm{PD}} = 1$ mm^2, $d = 2$ m, $\theta = 0$, $\eta = 0.8$, $\lambda = 850$ nm, $T_0 = 300$ K, $R_{\mathrm{n}} = 10\ \Omega$, $C_{\mathrm{s}} = 2$ pF, $C_{\mathrm{gs}} = 1$ pF.