Optimal detector size for Optical Wireless Communication links with wide coverage

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Laser-based and LED-based optical wireless communication has attracted a lot of attention in recent years due to advantages over radio RF-based systems. By using light, systems have advantages over RF systems such as immunity to RF interference, high security, lower cost and lower power consumption. LEDs have the advantage that illumination systems can be reused, and that modulation some extra power is needed but a DC bias is already available [1]. LEDs have limitations as their bandwidth is limited. Lasers have wider modulation bandwidths thus provide higher throughput. But in such case, a bottleneck of the system may shift to the receiver side.

A large number of papers describe optical wireless communication (OWC) systems that achieve high bitrates via lasers. Examples are [2]-[5]. However, the bit rate is not the only key performance indicator. The coverage area is another key parameter for a wireless link. Typically, it is easier to achieve a high data rate if the positions of the transmitter and receiver are fixed, the coverage area is confined to very small area and the receiver and transmitter can be highly directional. When the receiver has to receive signals over a wide range of possible angles and at the same time needs to achieve a high signal to noise ratio, an optimization may be needed. Choosing a laser diode as light source rather than a LED improves bandwidth. However, the detector may become a bandwidth bottleneck.

The size of the optical detector is a critical system design parameter. Smaller photo diodes may affect performance. Large detectors can capture more light, but increasing the size affects the bandwidth as its junction capacity grows. According to capacity expressions, the throughput typically grows linearly with bandwidth if the signal-to-noise ratio stays constant. On the other hand, for a given bandwidth, the throughput grows logarithmically with the signal-to-noise ratio. The detector size appears to have an optimum value. An optimization algorithm for the area of the detector in the OWC system can improve the performance of the system designs.

We model our optical system with a transmitter that emits power $P_{T,opt}$ into a beam coverage area A_B. The light intensity across the beam adheres to a certain profile. A Gaussian light distribution is commonly encountered. Here the peak intensity is highest in the center of the beam and gradually decreases with the distance. Such beams do not have a sharp border. We nonetheless denote A_B as the area with a radius r_0 where the light intensity of the beam falls down to $1/e^2$ of the peak irradiance. If the detector size A_D is smaller than the beam size A_B, total received power of the laser beam with Gaussian distribution with perfect alignment of the system is

$$P_R = P_{T,opt}\left(1 - \exp\left(-\frac{A_D}{A_B}\right)\right) \quad (1)$$

Thus, the path loss is $h = 1 - \exp\left(-\frac{A_D}{A_B}\right)$. Gaussian laser beams are widely used but a uniform distribution may be more attractive for many applications, or can be easier to treat mathematically. Particularly in multiuser OWC systems, spill-over into other cells is not desired and performance changes over position [6]. Users will not share the same connectivity experience.

So, we will also consider beam for which the irradiance is constant within its area A_B but equals to zero outside the beam. As the detector receives photons over its area A_D, with constraint that $A_D \ll A_B$, the total received power is simply

$$P_R = \frac{A_D}{A_B} P_{T,opt} = \frac{A_D}{\pi D^2 \tan^2\varphi} P_{T,opt} \quad (2)$$

Here the second equality models the beam divergence as φ. The power $P_{T,opt}$ is spread into a cone starting as a point at the transmitter, widening into a circle at a distance D reaching its receiving end with radius $D\tan\varphi$. The surface area of that beam coverage area is $\pi D^2 \tan^2\varphi$. For a more detailed discussion of path loss and (free-form optics) beam distributions that outperform Lambertian models, we refer to [7]. Here, we assume a uniform irradiance.

On the receiver side, we will consider a photodiode (PD) that is terminated with an matched amplifier, thus that has an input impedance that is matching and that does not largely affect the bandwidth of the photodiode. In further work, we plan to model the modulation signal and electrical noise spectra and their influence of a transimpedance amplifier (TIA) and the use of optics, of course subject to etendue restrictions.

The PD has a bandwidth that is defined by its internal parameters, in particular the source resistance R_S and capacitance of the p-n junction C_S. Having a low-pass nature, the bandwidth of the PD can be expressed as

$$f_{PD} = \frac{1}{2\pi R_S C_S} \quad (3)$$

Since the use of intensity modulation and direct detection (IM/DD) in OWC systems, M-PAM is greatly appealing with each symbol representing $m = \log_2 M$ bits. M-PAM has advantages in terms of power consumption and cost compared to other methods [8]. The throughput of such a system can be expressed as

$$R_b = 2mf_{PD} = f_{PD}\left[\log_2\left(1 + \frac{h^2\sigma^2}{N_0 \Gamma f_{PD}}\right)\right] \quad (4)$$

where h^2 denotes the pathloss and σ^2 is the signal variance. We also introduced a modulation gap

$$\Gamma = \frac{1}{3}\left\{Q^{-1}\left(\frac{\mathrm{BER}}{2}\frac{M\log_2 M}{M-1}\right)\right\}^2 \quad (5)$$

which can be derived from expressions of the bit error rate (BER) of M-PAM [8].

In this scheme we only use the bandwidth that is available within the 3 dB bandwidth f_{PD} of the photodiode. Other schemes can be used, such as the use of a transimpedance amplifier, or the use of pre-emphasis or post equalization. We will also discuss how modulating beyond the 3 dB bandwidth can improve the throughput.

As an example, Figure 1 shows that for such OWC system an optimal detector size exists. Its optimum value depends on system parameters, such as the intensity of the incoming light beam, its size and the noise floor. For this particular example, the beam size is 78.5 mm^2 with a uniform beam profile. We also noticed that a Gaussian beam produces very similar results. For larger detectors, although the signal-to-noise (SNR) ratio is better, the reduction in bandwidth has a stronger negative effect on the throughput.

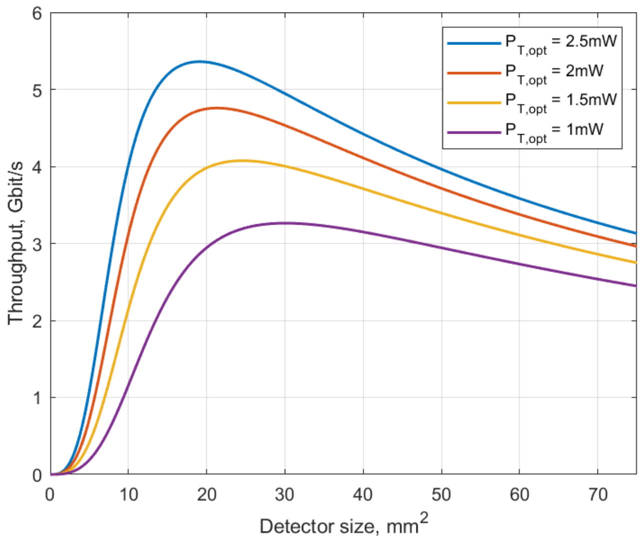

Fig. 1. Bit rate of the system that uses the flat frequency response range of the PD as a function of photo-sensitive area, for a noise floor of $N_0=10^{-17}$W/Hz.

The value of transmitted power $P_{T,opt} = 2.5\,mW$ is taken as maximum value of power within eye-safety limits for lasers in the visible spectrum [9]. For near infrared slightly higher powers are allowed. For lower transmit powers or for higher attenuation (large D), the optimal size is larger than for strong signals. We intend to look into more commonly-used front-end designs such as including TIA to the front-end side of the receiver to improve bandwidth and noise performance. In that case, a first evaluation still showed an optimum, but not as pronounced as for the modulation strategy described in this paper. In fact, power allocation strategies such as water filling with OFDM modulation allow further optimization of the signal power [8], though the use of unipolar variants OFDM comes with a power penalty [10].

To address a mass-market with indoor OWC system, miniaturization is an important aspect. Here we have shown that there is optimum in size, and we have quantified the performance penalty if further miniaturization is attempted. Our results also help to design control loops for systems in which the positions of the devices change and tracking of a beam would be needed.

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