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SINGLE-PHOTON SYSTEMS
APPLICATION NOTE

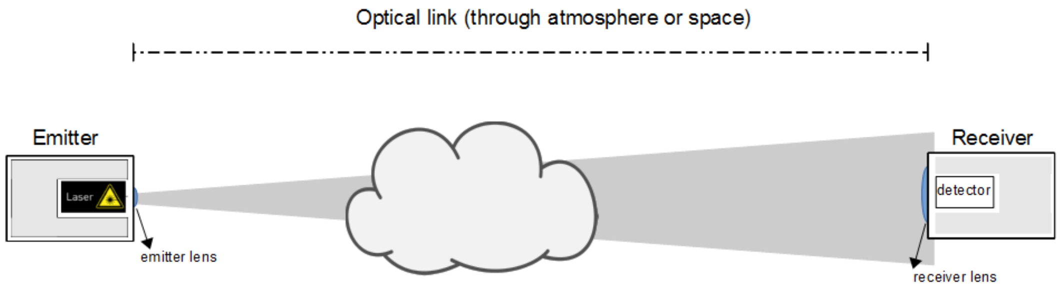
Single photon detectors used in free space communication

July 2016

Introduction

The increase in demand of high speed internet, video conferencing, live streaming, real-time imagery, and information technologies in general, put a strain on the current satellite communication systems based on radio frequencies. Optical technology has been considered as an alternative that can significantly improve the performance of free-space communication systems (such as radio-based communication) due to its advanced state. Indeed, national laboratories and industry have focused their efforts towards the development and commercialization of free-space optical (FSO) systems [1]. Among the advantages offered by FSO systems are: a higher operating frequency than radio systems, providing an increment in the channel capacity or data rate. (The data rates provided by FSO communication can range between 10 Mbps to 10 Gbps [2].) Another advantage is that FSO communication operates at smaller wavelengths than radio communication, resulting in a beam with lower divergence, and hence providing higher precision and intensity for a given transmitted power [2, 3]. Furthermore, FSO systems offer absence of interference between different data links allowing for a large number of channels [2-4]. Optical systems are typically low cost, reliable, have little power demand, and they are available in compact sizes, all desirable qualities for system components. FSO systems are composed of three main elements: emitter (laser), a receiver (detector), and an unobstructed line of sight between the two (communication channel) through which optical signals are sent, see Figure 1. FSO communication systems can be used in scenarios such as satellite communication, military applications, last mile access, intra-campus communication, disaster recovery, etc.

Figure 1 Typical free-space optical communication setup.



FSO communication, however, also faces technical challenges. First, these systems require a pointing and tracking system between emitter and receiver for alignment purposes [3, 4]. Pointing systems are expensive and the price is driven by its pointing accuracy and stability. A poor pointing system will cause a small overlap between the signal emitted and the effective detector area, translating into optical loss. Second, if the distance between emitter and receiver is too long or if climate conditions are not favorable (for example, due to rain or fog) the detector will not receive enough power from the incoming optical signals. In this case the communication will be impeded by the large optical loss in the communication channel. Certainly, one of the main challenges that FSO communication faces is its feasibility dependence on weather conditions, which determine the optical loss of the communication channel. The possibility to have an FSO communication system that is capable of operating in a low power regime (or equivalently, in a high optical loss regime) is highly desired. In particular, such FSO system would be more robust against limitations due to weather conditions. Alternatively, there exist communication systems that are, in general, benefited of a low optical power operation. This is because a low power operation allows adding a stealthiness factor to the communication that can be used to protect it by hindering the interception of optical signals. An FSO system that operates in a high optical loss regime is possible with the use of single photon detectors (SPDs) at the receiver. Using SPDs the signal arriving at the detector can be attenuated to the single photon level, and the detection will still be possible.

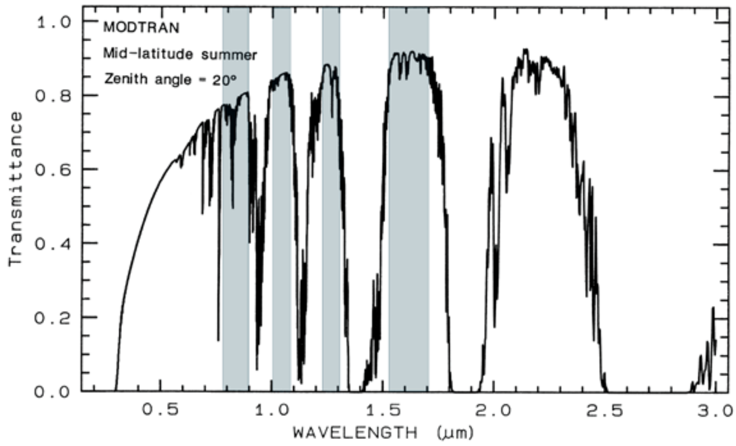
Link budget and noise

Any communication system requires a link budget and an estimation of noise in the system. In this section we will introduce the parameters of importance for the link budget and the noise present in an FSO system. Depending on the application, the communication channel is implemented through the atmosphere or through a combination of atmosphere and space. When a signal is transmitted through the communication channel it is attenuated due to different physical effects resulting in optical loss. The attenuation occurs regardless if the channel is established in space or atmosphere, albeit due to different causes. In space, the attenuation is due to divergence. In the atmosphere the attenuation is due to absorption and scattering, which in turn depends on the wavelength and the medium of transmission (rain, fog, etc). The noise present in an FSO system can be due to intrinsic noise of the components of the system or due to background radiation. The background noise will depend on the location and orientation of the FSO system, as well as the time of operation. In the following paragraphs we give a brief description of how each of these parameters impact the performance of an FSO communication system.

Wavelength

The choice of wavelength of the laser at the emitter depends mainly on three factors: the absorption (or losses) through the communication channel, the technology available to modulate the laser, and the technology available to detect the optical signals. When a signal transmits through space there is no absorption, vacuum does not impose any restrictions on the choice of wavelength. However, in the atmosphere, photons are absorbed and diffused by molecules, causing optical loss. Different wavelengths experience different absorption but a transmission window exists for visible light (400nm-800nm) and in the near infrared (around 1550 nm), making these wavelengths good candidates for FSO communication. It has been shown that the transmittance for 1550 nm through the atmosphere is higher than for visible light, see Figure 2, making this wavelength a good candidate for FSO communication.

Figure 2 : Atmospheric transmittance as a function of wavelength. Visible and near-infrared communication windows have been highlighted. Figure from [6].



Another wavelength dependent effect that causes loss is scattering. In the visible and ultraviolet range air molecules and haze cause Rayleigh scattering. At near-infrared wavelengths aerosol particles, such as fog and haze, will cause Mie scattering. As FSO communication depends highly on weather conditions, it is necessary to find out if there are any advantages to using visible or near-infrared wavelengths under non-ideal conditions.

For light fog, the attenuation due to scattering is less for 1550 nm than for shorter wavelengths such as 850 nm [2]. This makes 1550 nm more suitable for FSO implementations under these conditions.

In fact, near infrared wavelengths offer an additional two advantages over visible light in FSO communication. First, the choice of wavelength should comply with international safety specifications regarding the allowed output power of the laser [5]. The highest possible power is desired because it increases the probability of transmission of the signal in the communication channel. For a higher probability of transmission it is possible to achieve a higher distance of communication. Alternatively, if the distance between emitter and receiver is fixed, increasing the emission power of the laser increases the signal to noise ratio. According to the international standards for laser safety, a Class 1 laser is safe under all conditions of normal use and a Class 1M laser is safe for all conditions of use except when passed through magnifying optics such as microscopes and telescopes. For Class 1 lasers the maximum allowed CW output power is 10 mW for 1550 nm and about 1 mW for 760 nm [5, 6], benefiting the infrared wavelength. The second advantage of infrared wavelengths is in relation to infrastructure. Existing communication networks based on optical fibre operate for the near infrared wavelengths, specifically for 1310 nm and 1550 nm. The vast communication network consists of fibre links that extend throughout the world, interconnecting different countries. Choosing to work with signals at 1550 nm is the natural choice to establish an interface between FSO communication and existing communication systems based on optical fibre.

Divergence

Another source of loss in an FSO communication system is divergence. Divergence causes an increase in the size of the beam spot as a function of the distance from the aperture where the beam originates. The divergence of the beam increases with wavelength, and it decreases as the emitter lens increases in size. As an example, if only divergence is considered, a beam emitted in space at 1550 nm with a lens aperture of 0.1 m will expand to 11 m in diameter after a transmission distance of 600 km. Optical loss will be caused if the diameter of the telescope at the receiver does not match the diameter of the beam due to signal clipping, see table 1. The assumption of a large telescope that matches the beam diameter after its propagation through a long distance, however, is unrealistic. Unfortunately, divergence is not the only source of beam spreading, atmospheric turbulence also causes beam spreading, adding to the optical loss of the channel.

Pointing Error

If emitter and receiver move relatively to each other, for example in the scenario of a satellite moving with respect to a ground station, the FSO system must also have alignment capabilities. This is achieved with a pointing, acquisition, and tracking (PAT) system. A PAT system employs two optical beams to perform the alignment needed in the FSO system. The inherent pointing error of a PAT system will introduce optical loss in the FSO system. While divergence leads to more optical loss at longer wavelengths, it will also reduce the loss due to pointing error. This is because for a larger wavelength the divergence will cause a larger beam size at the ground, compensating for the poor pointing precision. One can see in table 1 the respective values of optical loss due to divergence and pointing error for two different wavelengths. The value of 10 µrad for pointing error that we used in this example is challenging however feasible in a micro satellite [8]. A six unit CubeSat could be equipped with a pointing and tracking system with pointing errors of ±90 µrad [9], this would lead to an optical loss of -29 dB and -35 dB for 1550nm and 760 nm respectively.

Atmospheric turbulence

One more factor that contributes to loss in a FSO communication system is atmospheric turbulence. Turbulence is due to local temperature variations and it causes fluctuations of the index of refraction in the communication channel. Atmospheric turbulence translates into intensity fluctuations; beam spread and beam wander [8]. Of these effects, beam spread and beam wander are sources of loss. Beam wander can effectively be treated as beam spread as it causes spatial beam fluctuations. Intensity fluctuations are the result of the propagation of the signal through the atmosphere and are known as scintillation. These fluctuations can be spatial (speckle) or temporal (twinkle). Establishing a communication channel with a satellite can be done in two different configurations. The signal can be emitted from the satellite to the ground station (downlink) or from the ground station to the satellite (uplink). An uplink has the advantage of allowing a larger transmitter system and gives opportunity for upgrades after the launch of the platform. However, in an uplink the dominant factor for loss is beam spreading due to turbulence [2, 8]. This is because the effect of atmospheric turbulence occurs closer to Earth, in the first 20 km of the atmosphere. In contrast a downlink has the advantage that it is much less sensitive to beam spreading due to atmospheric turbulence. For a downlink the dominant factor for loss is divergence. For this reason, there is an advantage to placing the emitter at the satellite, rather than at the ground station. This configuration is also optimal to place a large receiver telescope on a ground station to reduce losses due to signal clipping. In addition to optical loss the atmospheric turbulence will cause temporal dispersion of the optical pulses, the time jitter across 600 km in a satellite pass has been estimated to be on the order of 50 ps [8,10]. In the following table we present the link budget for a satellite located in a low earth orbit, at an altitude of 600 km. The emitter aperture is assumed to be 0.1 m and the pointing error of the system is assumed to be 10 µrad. The detection efficiency is assumed to be 20% for the detectors at 1550 nm, and 70% for the 760 nm wavelength. We assumed a collection efficiency of the optical system at the receiver of 50%.

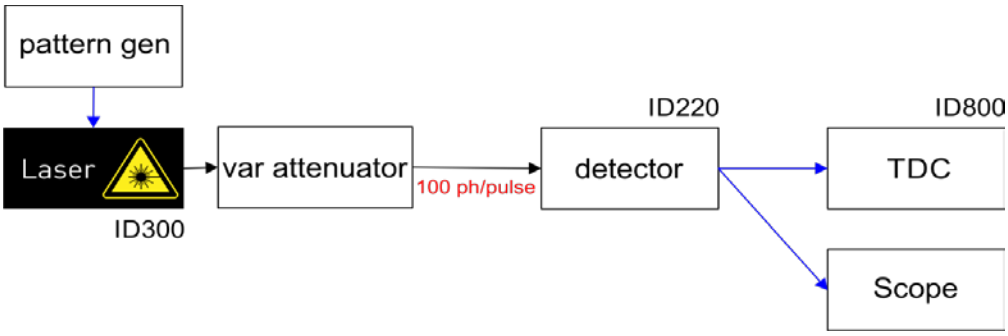
Table 1. Link budget for a LEO satellite placed at a 600 km orbit and with an emitter of Ø=0.1m

	loss at 1550 nm	loss at 760 nm
Transmittance	3	4
Divergence	27	21
Pointing error (10 µrad)	5	10
Collection & detection efficiency	10	5
Total loss	45	40

Noise

Noise imposes a limitation on the signal to noise ratio that can be achieved. The two main sources of noise in an FSO system using single photon detectors are intrinsic dark counts and background radiation. The amount of false counts due to background light will depend on the wavelength that is chosen for the communication, and the location of the ground terminal (urban or rural environment). Nevertheless, the effects of background light can be minimized if temporal and spectral filters are used in the system. The use of optical fibre coupled with the detector minimizes the possibility of having a detection originating from stray photons. Temporal filtering can be performed by synchronizing the opening (activation) of the detectors with the arrival of a signal. A specific implementation of temporal filtering is easily achieved through the use of window gates or via autocorrelation (with an ID 800) and a computer. Using this technique one can achieve, for example, for a repetition frequency of 1 MHz, and a realistic detection window of 100 ps, a signal to noise ratio of 40dB. Finally, a spectral filter will allow reducing the instance of false counts. An ordinary filter of 1 nm can be used to select the adequate spectral window chosen for communication. An additional argument for choosing near-infrared wavelengths is the effects of scattering. False counts that are due to scattering will be less likely for near infrared wavelengths than visible wavelengths because the scattering scales as λ^{-4}.

Figure 3: Test setup for a simple communication protocol: a pattern generator creates a repetitive sequence of 32 bits. This is sent to an ID300 laser, which emits a 300ps pulse to represent each "1" bit. A variable attenuator is used to simulate the link budget. The receiver is composed of an ID220 detector followed by an ID800 TDC.



Single photon detectors

Single photon detectors (SPDs) are a good solution to the detection of low intensity signals in FSO communication systems. As their name states, SPDs are capable of detecting the presence of a single photon with extreme timing accuracy (down to 50ps). This high timing accuracy helps to distinguish synchronous signals from noise, which has a random time of arrival. Alternatively, several bits may be encoded on a single photon, for example using pulse-position modulation (PPM), it is possible to encode bits onto a single photon, if it is sent during time and the detector has resolution . E.g. 14 bits may be encoded in a single photon if one is sent every 1.6µs and the detector has a 100ps resolution. In this example, 8Mbps may be sent with approximately 1pW (-90 dBm) of receiver power[1].

A simpler encoding consists of sending a laser pulse to represent a "1" and sending no laser pulse to represent a "0". For example, one may send a bit every 2µs, achieving a bit rate of 500kbps. As bits may be sent synchronously, any detection outside of the expected time-slot can be labelled as noise, eliminating errors due to noise.

We performed a test of this type of encoding using the setup shown in Figure 3. Results can be seen in Figure 4.

Depending on the exact protocol employed, noise conditions and link budget, the choice of optimal detector may be different. The most important decision to make is between a free-running or gated detector.

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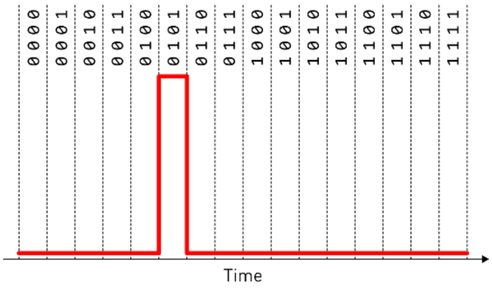
[1] Using a 10% detector efficiency, a wavelength of 1550nm

Figure 4: example of pulse-position-modulation (PPM) where the arrival time of a photon may encode several bits (4 bits in this example). The above pulse represents the value 0101.



Free-running detectors

This type of detector is active all the time, as soon as a photon is detected, however, the detector discharges and remains off for a certain time (typically 1µs-10µs). This effect limits the maximum number of counts that the detector may have (e.g. to 1Mcps). If there is a strong environmental noise component (e.g. stray light), several of the possible counts will be taken up by noise instead of signal. Although noise can be eliminated in postprocessing, e.g. by looking at the photon arrival time, having a dominant noise component will limit the maximum number of signal counts that can be measured. The advantage of free-running detectors is that all synchronization can be done in postprocessing, for example using a timestamping unit such as the ID800.

The ID220, ID230, and ID280 are free-running detectors for the infrared spectrum, whereas the ID100 and ID120 are visible free-running detectors.

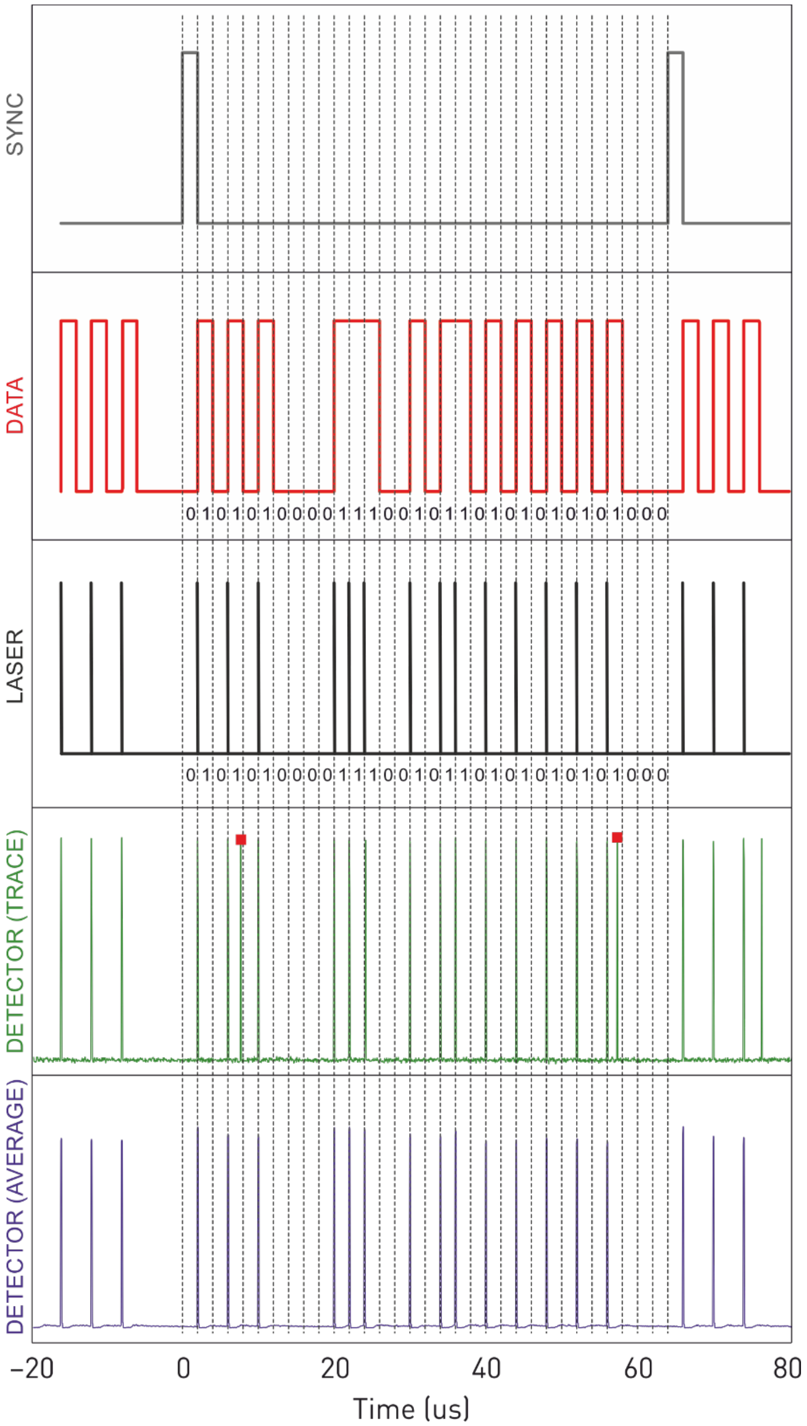
Gated detectors

Gated detectors may be set to be active or inactive according to an external synchronization signal, and may be set to become active for durations as low as 1ns. Any signal or noise that arrives outside of the gate will not affect the device, which will therefore not be affected by “dead-time”. This allows for communication to happen over a noisy channel, where the signal is buried in noise but can be selected by appropriate synchronization of the detectors. Gated detectors, such as the ID210 IR device or the ID110 visible device do have a free-running mode, however their performance is this mode is lower (e.g. higher noise) than that of native free-running devices such as the ID220 or ID230.

Superconducting detectors

Superconducting nanowire single-photon detectors (SNSPDs), such as the ID280, provide high efficiency and fast detection, however their superconducting nature requires them to run at <2.5K, i.e. in a cryostat. These detectors offer high performances but expensive, and may require more support than standard InGaAs devices.

Figure 5: simple communication experiment at the single-photon level. The detector trace displays two errors (labeled by a red square) that can be eliminated as they do not align with the expected photon



IDQ offers SPDs that work for both visible and near infrared wavelengths. The detectors can operate either in free-running mode or gated mode. SPDs feature low intrinsic noise, allowing a good signal to noise ratio, and hence are good candidates for communication systems. In addition, SPDs provide a timing resolution of 200 ps of the detected signal, this is particularly useful for implementations of communication protocols based on timing information such as the pulse-position modulation protocol. IDQ SPDs can be free-space coupled or coupled via an optical fibre (either single mode or multimode). Although the coupling of the signal into the detector can be a challenging task it has already been demonstrated. The project Lunar Laser Communication Demonstration showed the coupling of laser light emitted from a geosynchronous satellite at a distance of 300,000 km into a SPD located at a ground station. The satellite emitted light in the near-infrared wavelength. At the ground station four telescopes, each of 0.4 m in diameter, coupled the laser light into four multimode fibres connecting into the single photon detector [11, 12].

	ID230	**ID220**	**ID210**	**ID280**
Coupling	Multimode fiber 100 µm diameter	Multimode fiber 100 µm diameter	Multimode fiber 100 µm diameter	Singlemode fiber 9 µm diameter
Operation	Free-running	Free-running	Gated	Free-running
Detection efficiency	>25%	>20%	>25%	>70%
Dark count rate	<25 /s	<1000 /s	<10’000 /s	100 /s
Maximum count rate	500 kHz	1 MHz	5 MHz	15 MHz
Timing resolution	80 ps	160 ps	250 ps	70 ps

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