# Inter-Satellite Optical Communications Using Photonic Antennas

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***Abstract*—High data rate communication links are difficult to perform with radio frequency technology under the strict Size, Mass and Power (SMaP) constraints of small satellites. Transmitting data using the optical spectrum can permit higher data rates with more power efficient systems. Single photon avalanche diodes (SPADs) provide receivers with exceptional sensitivity levels, while Light-Emitting Diodes (LEDs) bonded to electronic driver chips provide digitally controllable optical transmitters capable of high bandwidth spatial and temporal modulation. Data rates of 100 Mb/s have been demonstrated at a sensitivity of -55.2 dBm, and ray-tracing simulations indicate ranges in excess of 1 km are feasible with simple optical systems. Additionally, the divergent nature of LEDs can provide a level of spatial coverage, relaxing pointing and alignment requirements. The low electrical power requirements and compact, semiconductor nature of these devices may therefore bring high data rate, high sensitivity communications to small satellite platforms.**

***Keywords–Light-emitting diodes; Single-photon avalanche diodes; Optical communications.***

## I. INTRODUCTION

In recent years, the development and deployment of small satellites has increased rapidly, with the development of the CubeSat standard greatly increasing academic and commercial access to space [1]. The future deployment of constellations, clusters or networks of small satellites necessitates high-speed inter-satellite data connections operating under strict Size, Mass and Power (SMaP) budgets. Communicating using the optical spectrum is an attractive alternative to radio frequencies due to the potential for high data rate systems with lower SMaP requirements [2]. Optical Inter-Satellite Links (ISLs) for large satellites achieve long ranges and Gb/s data rates using phase coherent laser communication methods, but are complex, costly and arguably too large and power hungry for small satellites [3].

Research in optical communications for CubeSats has been focussed on satellite to ground links using Laser Diodes (LDs) and fibre amplifiers as transmitters, however, similar systems have been proposed for ISLs [4] and a low-earth orbit (LEO) relay system [5]. The SMaP requirements for these communication systems are well within the capability of CubeSats, though they typically occupy at least a full 1U module and require significant battery power. Light-Emitting Diodes (LEDs) are a potential alternative device suitable for ISLs [6], bringing further advantages in SMaP constraints over laser systems, along with reduced complexity, longer lifetimes and lower cost. Gallium Nitride (GaN) micro-LEDs, LEDs with dimensions below 100 µm, show high modulation bandwidths and are an emerging technology for mass market applications. Previous research, including from our own group, suggests data rates comparable to the CubeSat LD systems are achievable [7]. Additionally, the angular divergent nature of LED emission may relax the tight pointing requirements found in laser systems.

Here, we present an experimental demonstration of high sensitivity, intensity modulated optical communications based on LEDs and silicon Single-Photon Avalanche Diode (SPAD) arrays. The advantage of such a system is in its simplicity and low SMaP requirements, while still achieving high sensitivities and data rates. To justify that the ranges, data rates, and angular tolerances are useful, ray-tracing simulations are presented.

In Section II, the experimental performance and SMaP characteristics of the communication link are described, followed by the ray-tracing results. Conclusions and further work are presented in Section III.

## II. MAIN RESULTS

The optical transmitter used in the experimental work is a single $99 \times 99$ µm² pixel, one of a $16 \times 16$ array of GaN micro-LEDs bump bonded to complementary metal-oxide-semiconductor (CMOS) control electronics. This device provides a mm-scale chip containing optical emission elements and driver electronics for independent control of every pixel. Fabrication and characterisation details of similar devices are reported in [8]. The emission wavelength is centred on 450 nm, primarily due to device availability. We note that such devices can be fabricated from the ultraviolet-C (UV-C) band to green using nitride alloys with wavelengths spanning many of the solar Fraunhofer lines, which may offer a low background noise channel [6]. The receiver is a $64\times64$ array of SPADs, arranged on a 21 µm pitch with a 43% fill factor [9]. The digital photon count signals from the pixels are combined through XOR trees and ripple counters, causing the device to operate as a digital silicon photomultiplier. An analytical discussion of the performance of SPAD arrays for optical communications can be found in Reference [10].

Details of the experimental arrangement and characterisation can be found in [11]. The resulting receiver sensitivity results, -60.5 and -55.2 dBm for 50 and 100 Mb/s, respectively, are shown in Figure 1 in red squares. Also shown are sensitivities achieved by complementary work from [9], where the same receiver was used for On-Off Keying (OOK) with a LD transmitter. The experimental results remain approximately a constant separation in dB from the standard quantum limit, set by the Poissonian nature of photon detection. The linear

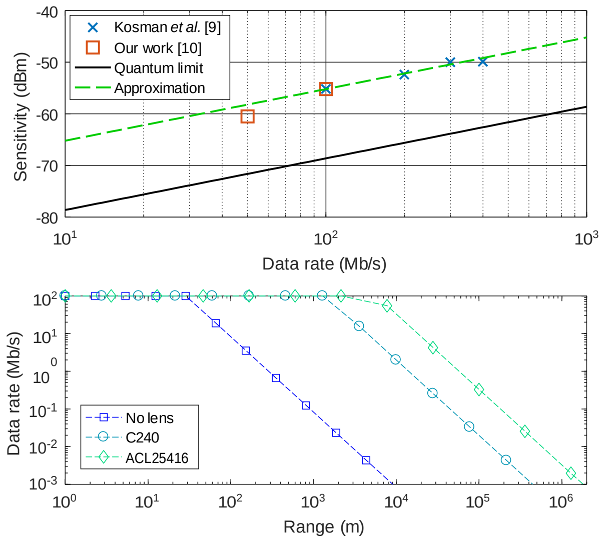


Figure 1. (a) Sensitivity limit for given data rates, experimental results and an approximation. (b) Achievable data rates in a point to point link, based on received intensities and the approximation in (a).

approximation shown in Figure 1 is used in the following simulations to estimate data rates for calculated levels of incident power.

Both the SPAD and LED chips are packaged and mounted on evaluation printed circuit boards (PCBs) where they are controlled and powered through field-programmable gate arrays (FPGAs) (Opal Kelly XEM3010/XEM6310). This results in transmitter and receiver package sizes of $14 \times 18.5$ cm$^2$ and $12.5 \times 20.5$ cm$^2$ respectively. Large parts of these evaluation boards are unnecessary for final applications, so a full transceiver system could potentially be developed on the CubeSat $10 \times 10$ cm$^2$ standard. The electrical power consumption of the full system under operation totals 5.48 W, with the majority consumed by the FPGA control systems. The system has not yet been optimised for power consumption, so this value can be considered an upper limit. Many CubeSats already employ FPGAs as part of their on-board systems, which could be used to produce and process the digital signals required, meaning only the micro-LED and SPAD arrays themselves would consume additional power, estimated to total less than 1 W.

In order to determine a range and coverage performance envelope for the system, ray tracing simulations were performed using Zemax OpticStudio®. The transmitter was specified as a $100 \times 100$ μm square, emitting 1 mW with a Lambertian profile typical of LEDs. A 10 cm diameter collection area was assumed at the receiver, likely the largest on-board collection area achievable with a CubeSat system. Three transmitter optical systems were considered: (i) no lens, (ii) collimation with the Thorlabs C240 lens used in the practical experiments, and (iii) collimation with a Thorlabs ACL25416 lens. The simulations were set up to determine intensity maps at varying ranges up to $10^6$ m. From the sensitivity approximation in Figure 1(a), achievable data rates can then be determined. The point-to-point results are shown in Figure 1(b). The intensity falls off following the inverse quadratic trend expected for the diverging beam, resulting in a reduction of achievable data rate. Note that the data rate has been upper-end clipped at 100 Mb/s as this is the limit achievable with the micro-LED transmitter operated in this manner. The results suggest the communication link can provide useful data rates over ranges up to 100's of kilometres. Range and data rate requirements will vary strongly with different satellite application scenarios, however these results are in line with other targets in the literature [4]–[6].

The collimation of light from the LED is still divergent, causing losses and limiting range. Importantly, this divergent light can be thought of as providing a level of coverage over an angular region, reducing the pointing accuracy required of the satellites. With the simulated intensity data, the achievable range for a given data rate at an angle from the transmitter can be determined. The results are shown in Figure 2 as angular plots. Note that the radial axis is logarithmic, and in the case of Figure 2(b) and Figure 2(c), the angular axis has been expanded in order to observe the profiles. With no lens, the micro-LED provides a very wide degree of angular coverage due to the Lambertian emission profile. For example, a 100 Mb/s link can be maintained at almost 60 degrees over a 10 m range. At 10 kb/s, the same angular coverage is maintained at approximately 1 km. The coverages provided by the collimated beams in Figure 2(b) and Figure 2(c) are much lower, at roughly 1 and 0.4 degrees for the C240 and ACL25416 respectively.

In a real deployment of this communication system on a CubeSat platform, additional constraints and factors will influence the performance of the ISL. Additional background light incident on the SPAD receiver increases the signal power required to maintain error free performance, so care would have to be taken to avoid background light sources through spectral and spatial filtering. In extreme cases, such as under direct solar irradiation, the receiver will likely saturate rendering the communication link useless. Secondly, the receiver optics have been simulated as a perfect collection area, a practical system will have physical limitations on achieving this, and some degree of loss will be inevitable. Finally, the performance of these bespoke devices in orbit, with potential for cosmic ray damage, is unknown. Silicon devices have a long history in space applications, and the avalanche nature of SPAD operation may help in protecting them from catastrophic breakdown. GaN devices are less mature for space applications, though the fact that they function in spite of high numbers of crystal dislocations suggests some degree of resilience to defect-causing damage from charged particles.

## III. Conclusion

In summary, a simple, low SMaP and high sensitivity communication link based on micro-LEDs and SPADs provides an attractive platform for CubeSat ISLs. The link distance and coverage simulations shown here suggest ranges up to 100s of kilometres are achievable with significantly relaxed pointing requirements compared to laser systems. Future experimental work will initially focus on a practical demonstration of communication at longer ranges ($>$ 100 m) through air. Significant work will be required to build a system suitable for testing in orbit on a CubeSat, primarily in developing an interface with on-board computer systems and adjusting hardware to the correct form factor. Once a final system has been developed, raytracing simulations with accurate parameters, such as emitted power, collection aperture and chosen optics, can be performed

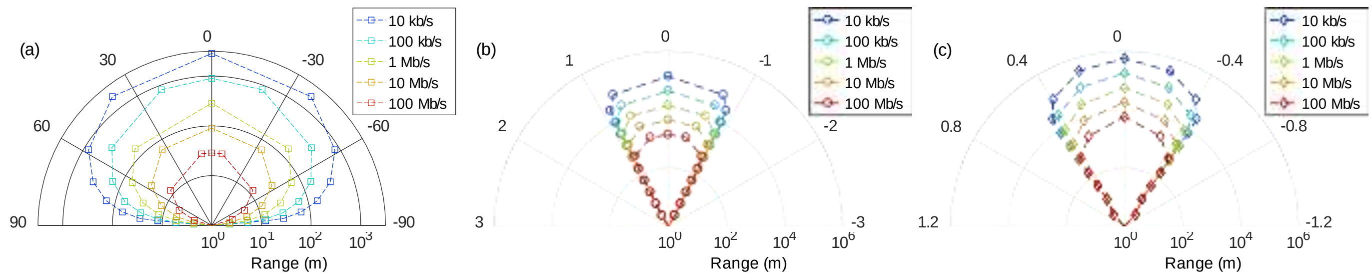


Figure 2. Angular coverage and range performance at data rates from 10 kb/s to 100 Mb/s for (a) no lens, (b) C240 and (c) ACL25416 cases. Note the angular ranges in (b) and (c) have been adjusted to aid visualisation of the narrow beam cases.

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