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# Extremely Low Power Quantum Optical Communication Link for Miniature Planetary Sensor Stations

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**In this paper a very low power optical communications system is addressed that could be developed specifically for creating networks involving a planetary lander and fixed or mobile sensor stations that could be as small as 1 cm$^3$. The communication system is a variant of photon-counting based communications. Instead of counting individual photons, the system only counts the arrival of time coincident sets of photons. Using sets of photons significantly decreases the bit error rate because they are highly identifiable in the presence of ambient light. An experiment demonstrating reliable communication over a distance of 70 m using less than a billionth of a watt of radiated power is presented. The experiment also compares this technique to traditional photon counting and successfully demonstrates that time coincident photon communications can achieve an equivalent bit error rate at a signal-to-noise ratio that is 5 to 7 dB lower than what is needed for classical photon counting communication. The components used in this system were chosen so that they could in the future be integrated into a cubic centimeter device.**

## Nomenclature

| | |
|---|---|
| *BER* | bit error rate (non dimensional bit errors/s) |
| $f$ | frequency (Hz) |
| $\langle N(1) \rangle$ | average number of photon coincidences for a "1" bit value |
| $\langle N(0) \rangle$ | average number of photon coincidences for a "0" bit value |
| $R_n$ | rate of signal photons detected at photon counter n (non dimensional counts/s) |
| $r_c$ | rate of photon coincidences owing to ambient light (non dimensional counts/s) |

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| | |
|---|---|
| $r_n$ | rate of ambient noise photons detected at photon counter $n$ (non dimensional counts/s) |
| $SNR$ | signal-to-noise ratio |
| $t$ | threshold value to differentiate a "1" bit value from a "0" bit value for on off keying (in counts) |
| $T_p$ | pulse period (s) |
| $T_s$ | bit period (s) |
| $\alpha$ | photon counter quantum efficiency |
| $\beta$ | the fraction of transmitted photon pairs captured by the receiver |
| $\delta$t | coincidence time window (s) |
| $\lambda$ | wavelength (nm) |

## I. Introduction

ONE concept for planetary exploration involves using a sensor web that may include many small sensor elements, either on robotic or fixed platforms, which can cover more ground than a single conventional lander. In addressing this vision, NASA has been challenged in the National Nanotechnology Initiative to research the development of miniature robots built from nano-sized components [1]. These sensor platforms have very significant challenges, such as mobility and communication, given the small size and limited power generation capability. The research presented here has been focused on developing a communications system that has the potential for providing ultra-low power communications for robots such as these. In this paper an optical communications technique that is based on transmitting recognizable sets of photons is presented. In previous research, pairs of photons that have an entangled quantum state have been shown to be recognizable in ambient light, even when the ambient background noise is significantly larger than the signal [2–5]. The main drawback to using entangled photons is that they can only be generated through a very energy inefficient process. In this paper a new technique that generates sets of photons from pulsed sources is described and an experimental system demonstrating this technique is presented. This technique of generating photon sets from pulsed sources has the distinct advantage in that it is much more flexible and energy efficient, and is well suited to take advantage of the very high energy efficiencies that are possible when using nano scale sources. For these reasons the communication system presented in this paper is well suited for use in very small, low power landers, and rovers.

## II. Communication System Based on Photon Pairs

The general objective of these research activities is to develop a communication system based on time coincident photon pair communication that can eventually be built into a miniaturized transmitter that is very efficient in terms of the amount of electrical power used to transmit a bit of information. The generation of quantum entangled photons is extremely energy inefficient and is not as feasible for usage in low power devices. For this communication method to be used, it is necessary to develop a more efficient method for generating the signal photon pairs. There is no known energy efficient method to create photon pairs that share a quantum state, and are hence "quantum entangled" (QE). However, the QE communication method can be emulated. The QE communication method works because of the generation of inherently time coincident photon pairs that have highly correlated wavelengths and polarizations. It is possible to build a transmitter that efficiently generates photons with these correlations. The primary subject of this research is a transmitter concept that can generate correlated photon sets, which look like entangled photons to a receiver, in an efficient manner.

A time coincident photon communication system that generates pairs of photons is shown as a block diagram in Fig. 1. In this figure the details of how the beams are combined at the transmitter and likewise separated at the receiver are left out so that the basics of the signaling method can be understood. To transmit a "1" bit value, photon sources 1 and 2, which are separately identifiable by either wavelength, polarization or both, are pulsed at the same time to send pairs of photons to the receiver. A "0" is likewise transmitted by pulsing sources 3 and 4 at the same time. The sources are pulsed several times during the bit period so that a significant count is recorded at the receiver. The pairs are detected by photon detectors 1 and 2 for a "1" bit value and 3 and 4 for a "0" bit value. Note that each of these individual sources and corresponding detectors will also be referred to as channels later in this paper. The coincidence detector circuits determine if pulses from the photon detectors occur within a coincidence time window. If the photon detections are within the window a coincidence is registered. If not within the window the

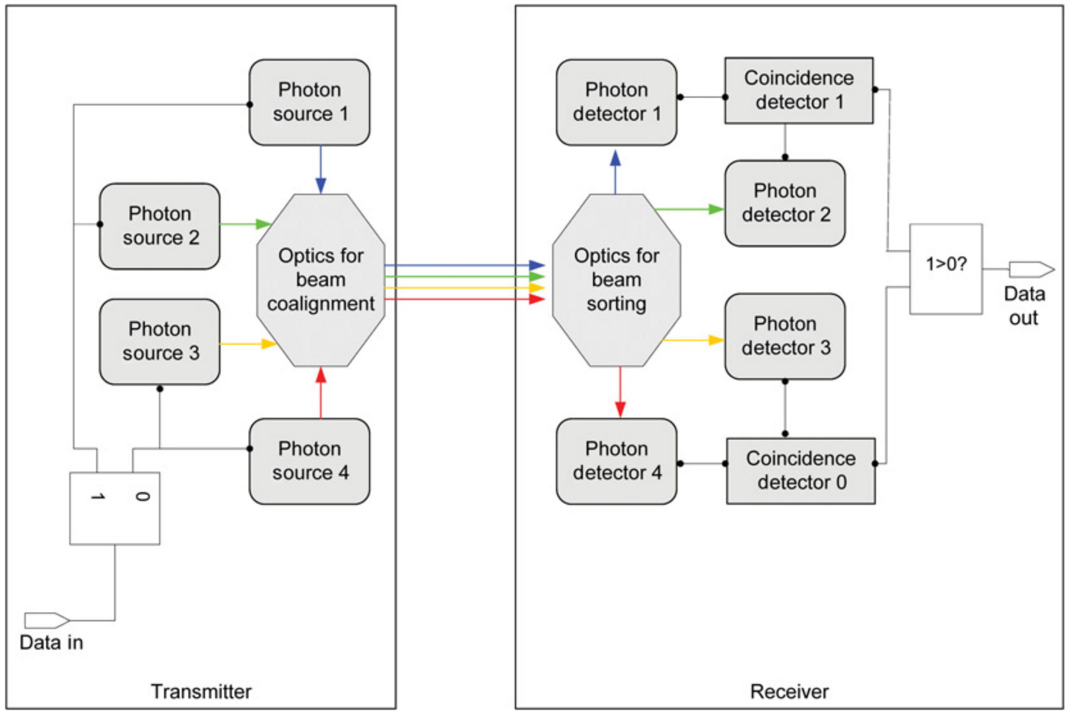


**Fig. 1 A time coincident photon communication system made from classical sources. A "1" data bit passed to the transmitter will repeatedly pulse photon sources 1 and 2 at the same time while a "0" bit will pulse photon sources 3 and 4 at the same time. The sources have particular wavelengths and polarizations so that they can be efficiently combined into a co-aligned beam at the transmitter and likewise sorted at the receiver. The coincidence detector 1 records the number of times during a bit period that photon counters 1 and 2 fire within the coincidence time window and likewise coincidence detector 0 records the coincidences of counters 3 and 4. If the count for coincidence detector 1 is greater than or equal to the count for coincidence detector 0 then a "1" bit value is recorded at the receiver, otherwise a "0" bit value is recorded.**

photon detections are ignored. The receiver then compares the number of coincidences from coincidence detector 1 to coincidence detector 0 to determine the value of the bit.

To convey an idea of the power levels that are achievable, at least in an ideal case, it is possible to estimate the power per bit of information transmitted for an integrated device that uses this signaling method. This calculation is best done by starting with the required signal at the receiver. We know from the experiments performed up until now that the communication system has a reasonably low bit error rate (BER) if the number of coincidences registered by the receiver is greater than 10 per bit [5]. Assuming a detector has a quantum efficiency of 70% means that the receiver must collect at least 14 photon pairs per bit to register 10 per bit. For the transmitter, it can be assumed, somewhat hopefully, that a very advanced nanolaser will have a 50% conversion efficiency of electrical to optical energy [6–9]. The transmission loss is already known as the range is bounded to the distance at which the transmitted beam falls off to 50% [4]. From these assumptions it can be estimated that 56 photon pairs/bit must be emitted from the transmitter to get 10 coincidences at the receiver. The electrical energy to generate these photons is equivalent to the energy of 112 photons per bit. The energy per bit is approximated by multiplying the number of photons, 112, by the energy per photon equal to $2 \times 10^{-19}$ J/photon at 1 $\mu$m wavelength. This comes to $22 \times 10^{-18}$ Joules. At a frequency of 100 kHz the power this transmitter uses is equal to 2.2 pico watts (pW).

It should be noted that several important basic problem in free-space laser communication are not covered in this paper. The problems caused by beam wander or atmospheric attenuation, common to all directional optical communication systems, still would have to be addressed. The problem of the transmitter and receiver finding one another is also a significant issue. The problem could conceivably be solved by the smaller sensor stations working with a larger relay station. This relay station would be large enough to transmit a locating beacon to the smaller stations to tell them where to point their data transmissions. The smaller stations would either be fixed or would travel slowly so that the relay station would know where to look to find the transmissions from the smaller stations. This concept has not been entirely worked out, as it has been the primary focus of this work to develop a very low power signaling technique recognizable in the presence of ambient noise.

### A. Transmitter

The block diagram for the transmitter concept is shown in Fig. 2. Data are modulated by a signal from an oscillator or clock. The modulated signal drives optical sources of different wavelengths or polarizations. These sources (which may be light-emitting diodes (LEDs), laser diodes, quantum wells, or quantum dots) can be driven with very small, and very fast pulses of electrical energy so that a pulse of photons is generated. The photons from all four optical emitters are sent coaxially along the same optical path to a receiver where they are separated according to wavelength and polarization state. Various optical configurations can be used spatially to superimpose the signals from all emitters along a common optical path, including dichroic beamsplitters, polarizing beam splitters, or a combination of a diffractive element such as a prism or grating and polarizers.

This method of communicating using correlated photons provides many possibilities for the assignment of physical parameters to bit values. Table 1 is a truth table defining the way in which the information bits are encoded. According to Table 1, when the receiver counts photons from wavelengths $\lambda_1$ and $\lambda_2$ in temporal coincidence that both have vertical polarizations, then the information bit is a “0”; when the receiver counts photons that are in horizontal polarization states, then the information bit is a “1”. Of course, other polarization coding schemes can be employed to achieve the same effect, such as orthogonal polarizations for a “0” and identical polarizations for a “1” and vice versa.

Note that by use of additional logic gates, a system can be devised to send up to 2 bits ($2^2$) of data to yield a possible of four combinations vs the two possible combinations shown in Table 1. The truth table for this configuration is shown in Table 2. For the communication schemes shown in Table 1 and Table 2, only two photons, one at each wavelength, have to be captured by the reciever. As only two photons have to make it to the receiver, this implies

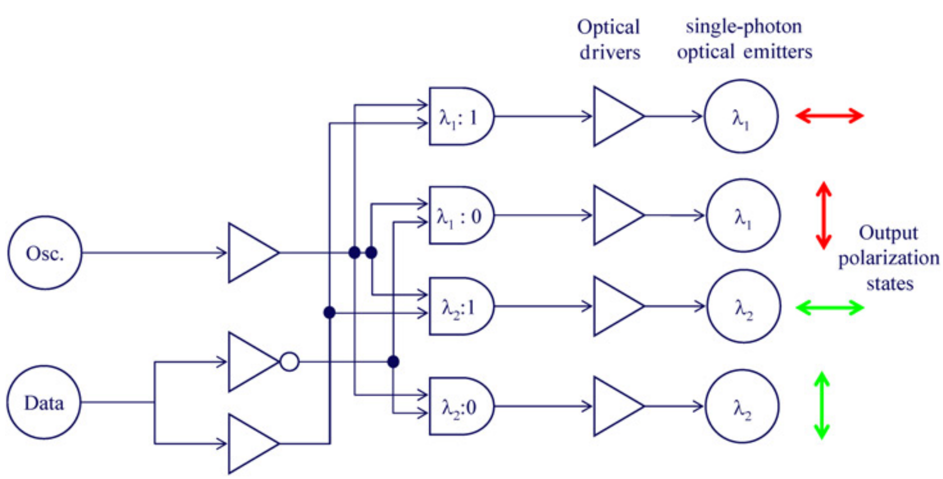


**Fig. 2 Schematic of the logic diagram for the multiwavelength time-coincident optical transmitter. The oscillator provides a steady stream of alternating low(0) and high(1) digital clock pulses. The data stream is sent to the appropriate AND gate which then determines which optical emitter to fire. The logic states are shown in the truth table in Table 1. The optical emitters can be, but are not limited to LEDs or diode lasers, quantum-dots, and so on. Depending on the emitter that is fired, each has a certain wavelength, or spectral channel, and polarization associated with it. In this way, both wavelength and polarization states are used effectively to increase the signal-to-nose ratio (SNR) for single-photon data transmissions.**

**Table 1 Bit coding table for schematic shown in Fig. 3. Light emitters fire in pairs with complementary wavelengths and identical polarizations**

| Oscillator (clock) | Data input | Optical Output (λ, polarization) |
|---|---|---|
| 0 | Any | 0 |
| 1 | 0 | $\lambda_1$ vertical, $\lambda_2$ vertical |
| 1 | 1 | $\lambda_1$ horizontal, $\lambda_2$ horizontal |

**Table 2 Truth table or logic chart for an alternate embodiment (not shown) but based on Fig. 3 where up to 2-bits (4 states) of information can be sent at a time through the use of perpendicular polarization states of $\lambda_1$ and $\lambda_2$**

| Oscillator (clock) | Data input | Optical Output (λ, polarization) |
|---|---|---|
| 0 | Any | 0 |
| 1 | 0,0 | $\lambda_1$ vertical, $\lambda_2$ horizontal |
| 1 | 1,0 | $\lambda_1$ horizontal, $\lambda_2$ vertical |
| 1 | 0,1 | $\lambda_1$ vertical, $\lambda_2$ vertical |
| 1 | 1,1 | $\lambda_1$ horizontal, $\lambda_2$ horizontal |

that very few photons must be transmitted from the transmitter. The actual number of photons transmitted depends on the reciever size and quantum efficiency, the distance of the transmission and the directional capability of the transmitter.

The experimental version of the 1-bit transmitter was built using commercial, off-the-shelf, components. The components used were chosen with an emphasis on their potential eventually to be incorporated into a very energy efficient monolithic device that is appropriate for a miniature robot. For example laser diodes have been used along with collimating optics limited to an aperture diameter of 1 cm. There were two laser diode sources at 669 nm and 2 at 673 nm. They were arranged so that one laser of each wavelength was polarized vertically and the other was polarized horizontally. The lasers were pulsed 10 times per bit and the pulse duration of the laser pulses was approximately 10 ns. This pulse duration is the lower limit of the commercially available diodes.

### B. Receiver

In Fig. 3 the receiver diagram is shown with more detail of the optical components. The receiver has a 50.8 mm diameter telescope to collect the photons and also collimate the received beam for the rest of the optical system. Immediately after the collection optics is a bandpass optical filter, denoted $\lambda_1$, that passes a 2 nm bandwidth centered at 669 nm. The filter reflects the 673 nm photons, which are guided to another 2 nm bandpass filter, denoted $\lambda_2$, centered at 673 nm. With this set of filters the photons of wavelength 1 go to one set of single photon detectors and the photons of wavelength 2 to a separate set of single photon detectors. The single photon detectors are Geiger mode avalanche photodiodes that have 70% quantum efficiency, 50 ns off time after each photon and are relatively low noise with just a few hundred dark counts. These detectors have been used to achieve nearly 1 photon per bit free space communication but have until now been limited to situations with "little or no background noise" [10]. After the filter, the photons of wavelength 1 are separated by a polarization beam splitter (PBS) into horizontal and vertical polarizations and then detected by photon counters. The photons of wavelength 2 are likewise separated by polarization and detected.

The coincidence electronics determine which photon counters fire at the same time and thereby decode the data in bits of ones and zeros. The coincidence electronics have been built using a field programmable gate array and the coincidence time window is 11.75 ns. The coincidence time window is influenced by the laser pulse duration. It cannot be too small compared to the pulse duration or a photon from one source early in the pulse will not be time coincident with another photon from its paired source late in the pulse. The number of coincidences resulting from

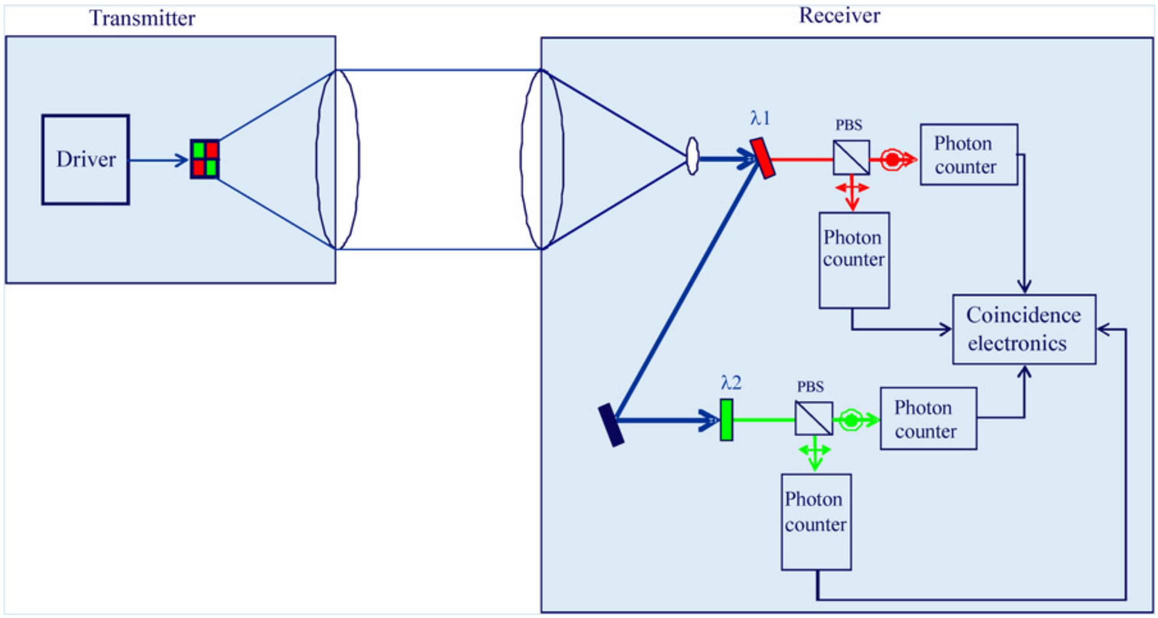


**Fig. 3 In this schematic the transmitter is shown working in conjunction with a receiver. The internal optics of the receiver that sort the received photons starts with a telescopic front optic that collects and collimates the received photons. After this there are two filters, one that passes photons in band 1 while reflecting all other wavelength photons and a second that passes photons in band 2. Behind the two filters are polarization beam splitters (PBS) that have extinction ratios of 1000:1 which sort horizontally polarized photons from vertically polarized photons. The front end optics therefore sorts the beams so that the photon counters only see photons of a particular wavelength and polarization.**

noise photons is directly proportional to the coincidence time window, denoted as $\delta t$, and is approximately equal to

$$r_c \approx \prod_n r_n \; \delta t^{n-1} \; T_s \tag{1}$$

where $r_n$ is the noise photon count rate for detector $n$, $n$ is the number of channels used for coincidences, and $T_s$ is the bit period [11]. Additional noise reduction would have been possible if a coincidence time of 1 ns were used but this would have resulted in significant signal loss because the laser pulses were of 14 ns duration.

### C. Bit Error Rate Calculation

The idea of using quantum optics for communication in very low signal-to-noise ratio (SNR) environments has been around for some time. Mandel [2] first proposed one such system in 1984 and a demonstration experiment was performed by Hong et al. [3] in 1985. In this experiment, pairs of polarization entangled photons were generated and transmitted to the receiver over two beams of light that were on–off keyed with the data. The experiment demonstrated that highly correlated time coincident pairs of photons are highly recognizable in the presence of noise from ambient light. From Shannon information theory we know that the larger the noise, or background light in this case, in a discrete channel, the lower the rate at which information can be transmitted. If the noise level were to exceed the signal then the information becomes useless. The obvious way to overcome the noise for successful communication is to increase the signal strength. However with a fixed signal strength, which is below the ambient noise, the proposed optical system using quantum entangled photons for communication has merit. By modifying the equations derived by Mandel it is possible to derive a comparison between this non-classical photonic communication system and a single beam on–off keying (OOK) communication system (classical photonic communication).

From Mandel's, Hong's and Friberg's analysis [2,3] the BER for the quantum entangled photon pair communication can be derived. It has been shown that the total rate at which coincident photons are counted is a sum of the entangled photon pairs that are counted as well as the counted uncorrelated photons that accidentally overlap. The rate at which entangled photon pairs are counted, $R_{\mathrm{CE}}$, is the product of the rate at which one of the conjugate photons is counted at one detector, $R_{1,2}$, and the probability that the second photon of the pair will be detected at the other detector, which is equal to the quantum efficiency of the other detector $\alpha_{2,1}$. These rates are equivalent because the entangled photons are always produced in pairs

$$R_{\mathrm{CE}} = R_1\,\alpha_2 = R_2\,\alpha_1 \tag{2}$$

The accidental photon coincidence rate is the sum of the ambient noise photon rate for each detector, $r_{1,2}$, and also the rates, $R_1(1-\alpha_2)$ and $R_2(1-\alpha_1)$, which account for the case where one entangled photon of a pair is detected while the second one is not. From the accidental and conjugate photon coincident rates we have the following photon coincidence rate

$$R_c = [(1-\alpha_2)\,R_1 + r_1]\,[(1-\alpha_1)\,R_2 + r_2]\delta t + R_1\alpha_2 \tag{3}$$

where $\delta t$ is the time window in which the arrival of a photon at both detectors is registered as a coincidence.

When data are transmitted using on/off coding, the average number of coincidences registered when the transmitter is on, $\langle N(1)\rangle$, which represents a one data bit, is described by the equation

$$\langle N(1)\rangle = [(1-\alpha_2)R_1 + r_1][(1-\alpha_1)R_2 + r_2]\delta t T_s + R_1\alpha_2 T_s \tag{4}$$

where $T_s$ is the time period for each bit. When the transmitter is off, which represents a zero, the average number of photon coincidences detected, $\langle N(0)\rangle$, is

$$\langle N(0)\rangle = r_1 r_2 \delta t T_s \tag{5}$$

In contrast to quantum entangled photon pairs, the pulsed photon sources are not definitely produced in pairs. They instead can be designed so that both sources produce an average of one or more photons per pulse. The probability of a pair being detected during a pulse time $T_p$ is therefore equal to the product of the average counts at detector one and the probability a second photon will be counted by detector 2. The probability a second photon will be detected is a function of the quantum efficiency for detector 2, the ratio of pulses that contain at least one photon captured by detector 2 and also the ratio of the coincidence time to the pulse width. When a one is transmitted the average coincidences at the receiver owing to photons from the sources one and two will therefore be

$$R_1 \frac{\alpha_2 R_2}{R_p} \frac{\delta t}{T_p} \tag{6}$$

where $R_p$ is the pulse rate and $T_p$ is the pulse width. This equation is valid for $T_p \geqslant \delta t$, otherwise $\delta t / T_p = 1$. When a second photon of a pulsed pair is missed another contributor to coincidences are attributable to a photon from one of the transmitters being detected in coincidence with a noise photon expressed by

$$[(1-\alpha_2)R_1 r_2 + (1-\alpha_1)\,R_2 r_1]\delta t T_s \tag{7}$$

The last contributor to coincidences is attributable to accidental coincidences from ambient photons expressed by $r_1 r_2 \delta t T_s$. Adding all these contributions gives the average number of coincidences detected by detectors 1 and 2 when a "1" is transmitted

$$\langle N(1)\rangle = R_1\alpha_2 \frac{R_2}{R_p}\frac{\delta t}{T_p} T_s + [(1-\alpha_2)R_1 r_2 + (1-\alpha_1)\,R_2 r_1 + r_1 r_2]\delta t T_s \tag{8}$$

The noise that can contribute to a "1" being misinterpreted as a zero is only attributble to ambient photons being detected by detectors 3 and 4 and is

$$\langle N(0|1)\rangle = r_3 r_4 \delta t T_s \tag{9}$$

Because the data are coded in a symmetric fashion the equation for the average numbers of coincidence when a "0" is transmitted is the same as for a "1" only with photon counter 3 and 4 replacing the 1 and 2 subscripts

$$\langle N(0)\rangle = R_3\alpha_4 \frac{R_4}{R_p}\frac{\delta t}{T_p}T_s + [(1-\alpha_4)R_3r_4 + (1-\alpha_3)R_4r_3 + r_3r_4]\delta t T_s \tag{10}$$

and likewise the equation for noise when a "0" is transmitted is

$$\langle N(1|0)\rangle = r_1r_2\delta t T_s \tag{11}$$

The probability for an error when a 1 is transmitted is, as with the symmetric QE two-state coding

$$P(0|1) = P[N(1) \geqslant N(0|1)] \tag{12}$$

and likewise the probability for an error with a zero is

$$P(1|0) = P[N(0) < N(1|0)] \tag{13}$$

The probability of error therefore is the probability that a random value from the noise probability distribution will be equal or larger than a random value from the signal probability distribution. This probability that a random number from one distribution function is larger than a random number from another distribution function can be found by summing all of the probabilities for positive values in the difference between the two functions $z$. This is expressed for the case of a "0" bit error by

$$P[N(1|0) > N(0)] = \sum_{z>0} P[N(1|0) - N(0) = z] \tag{14}$$

The difference between Poisson variables has been shown [12]

$$P[N(1|0) - N(0) = z] = \mathrm{e}^{-(\langle N(1|0)\rangle + \langle N(0)\rangle)}\left(\frac{\langle N(1|0)\rangle}{\langle N(0)\rangle}\right)^{z/2} I_z\left(2\sqrt{\langle N(1|0)\rangle\langle N(0)\rangle}\right) \tag{15}$$

where $I_z(\,)$ is a $z$th-order modified Bessel function of the first kind. The probability of error for a "0" bit is therefore

$$P(1|0) = \sum_{z=1}^{\infty} \mathrm{e}^{-(\langle N(1|0)\rangle + \langle N(0)\rangle)}\left(\frac{\langle N(1|0)\rangle}{\langle N(0)\rangle}\right)^{z/2} I_z\left(2\sqrt{\langle N(1|0)\rangle\langle N(0)\rangle}\right) \tag{16}$$

In the same manner the probability of error for the "1" bit is found to be

$$P(0|1) = \sum_{z=0}^{\infty} \mathrm{e}^{-(\langle N(0|1)\rangle + \langle N(1)\rangle)}\left(\frac{\langle N(0|1)\rangle}{\langle N(1)\rangle}\right)^{z/2} I_z\left(2\sqrt{\langle N(0|1)\rangle\langle N(1)\rangle}\right) \tag{17}$$

The difference between the summation for the "1" bit error starting at $z = 0$ and the "0" bit error starting at $z = 1$ comes from an arbitrary decision to assign a tie in coincident counts as a "0" bit.

The BER is the average of the two error probabilities

$$\mathrm{BER} = \frac{P(1|0) + P(0|1)}{2} \tag{18}$$

In the subsequent experiments data is taken with one channel, as classical OOK, and two coincident channels with data encoded by OOK. In the two-channel case $\langle N_1\rangle$ is still calculated using Eq. (8) and $\langle N_0\rangle$ is calculated by Eq. (5). In the one-channel case $\langle N_1\rangle$ is simply the average number of photons detected during a "1" bit equal to $R_1T + r_1T$

and $\langle N_0 \rangle$ is the average number of photons detected during a "0" bit, equal to $r_1 T$. The error probability equations for OOK is [2,3]

$$P(0|1) = \mathrm{e}^{-\langle N_1 \rangle} \sum_{r=0}^{t-1} \frac{\langle N_1 \rangle^r}{t!} \tag{19}$$

$$P(1|0) = 1 - \mathrm{e}^{-\langle N_0 \rangle} \sum_{r=0}^{t-1} \frac{\langle N_0 \rangle^r}{t!} \tag{20}$$

where $t$ is the threshold value that differentiates a "1" bit value from a "0" bit value. The BER for these cases is then obtained using Eq. (18).

## III. Experimental test and results

This system has been tested in indoor free space communication experiments. The experimental setup diagram is shown in Fig. 4. The test was conducted in a hallway with the transmitter and receiver located next to one another.

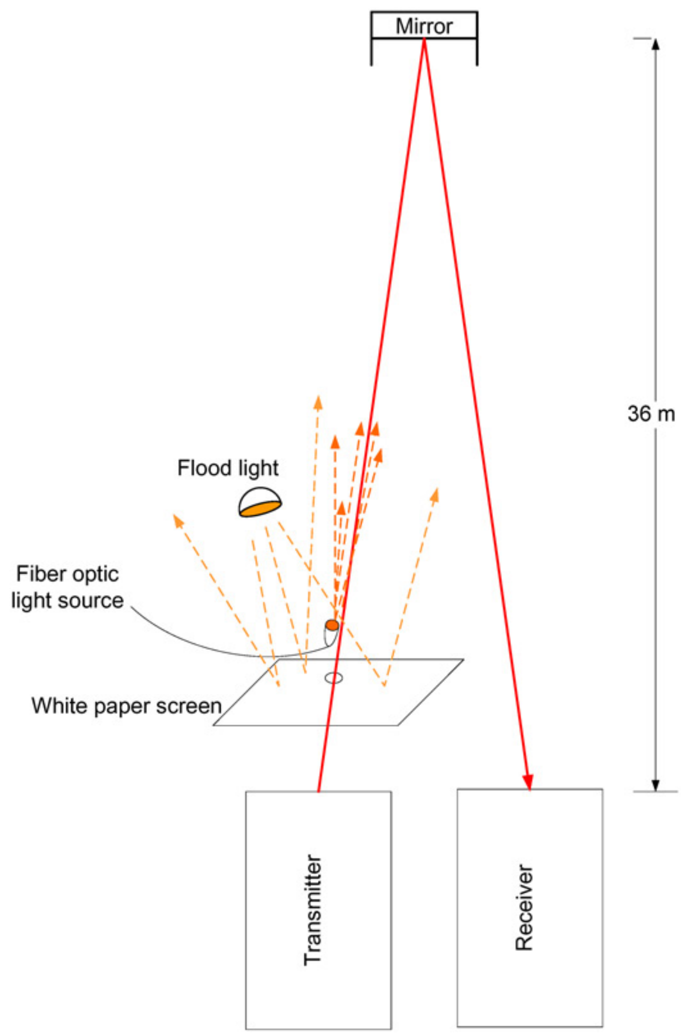


**Fig. 4 This figure shows the configuration of the ranged experiment. The experiment was performed in a hallway that allowed for a total of 72 m of distance between the transmitter and receiver.**

This allowed for the longest transmission distance and also made aligning the two easier. A white paper screen, with a small hole in it to allow the transmitted beam to pass through, was placed in front of the transmitter. This screen provided a uniform reflector so that the background light seen by the receiver could be controlled by illuminating it with different brightness lights. To achieve the highest ambient light levels a fiber optic light source was located next to the beam path and directed towards the receiver. The highest background light levels were similar to outdoors on a sunny day while the lowest were similar to outdoors with heavy clouds. In this experiment, the signal power for all configurations was attenuated by neutral density filters so that, for each channel, approximately one photon per pulse was detected at the receiver. The signal was kept constant for all experiments and the background light level was varied. Three experiment configurations were tested. The baseline configuration was just a single channel (no coincidence) that was used for traditional on/off keyed photon counting communication. In the second configuration photons were transmitted in time coincidence over two channels. A clock signal was transmitted and the bit values were encoded by OOK. The third configuration used four channels. In this configuration the data were keyed as shown in Table 1. The transmitted power for the single channel case was 180 pW, the two-channel case was 360 pW and for the four-channel case 760 pW.

There were several sources of experimental error. A systematic error was caused by the lasers not completely shutting off between pulses. With the lasers staying on between pulses, these additional photons add a bias to the measured signal level when they are actually a contribution to the noise level. This bias level was measured to be 24% of the overall signal level. Another source of error was caused by conditions in the hallway that were not ideal. There was a very significant temperature change between the room where the transmitter and receiver were located and the hallway the mirror was in. There was also considerable turbulence in the hallway from the heating and cooling system. This caused a significant amount of beam wander, on the order of 1.5 to 2 cm linear displacement, which was probably very similar to what would be encountered outdoors. It was observed that the multiple beams did appear to stay together as they moved which was expected as the beams were at nearly the same wavelength. There were no active measures taken in the transmitter or receiver to counteract this beam wander so it should be noted that this was a significant contributor to the BER.

In Fig. 5 a sample of the raw data from the single channel (top) and two channel (bottom) configurations is shown. The single channel data plots photon detections as function of time. The two channel data plots photon coincidence detections over time. The data rate was 100 Kbit/s so there were 10 microseconds of “on / 1” with photon pulses and 10 microseconds “off/0” without pulses. In the single channel case it can be seen that there are 10 microsecond time periods with more photon counts, and periods in between with less, but the contrast between these is not very strong. In the two-channel case, the 10 microseconds of coincidence counts are readily apparent as there is almost no noise between them. The data clearly show the noise immunity obtained by using coincident photon communication. The data however also show some periods where the two-channel coincidence counts are low. For example, in the two-channel data the period between 30 and 40 microseconds there are only four coincidence counts. With some low counts such as these it is apparent that signal loss owing to beam wander was probably one of the most significant sources of error.

The data taken in these experiments have been tabulated and graphed in Fig. 6 to show the BER as a function of SNR. Three data sets consisting of approximately 10 Kbits of data were transmitted through the system and the BER was measured for each data set. In Fig. 6, each data point is the average of the three BER measurements that were taken for each condition point and the error bars show the ±one-sigma range calculated from the three BER measurements. SNR was measured by independently counting the number of noise photons received by the individual detectors while the background lights were on and the transmitter was off and also by counting the number of signal and noise photons received when the transmitter and background lights were both on. The noise measurement was subtracted from the signal with noise measurement to leave the signal photon count. Then SNR was determined from the ratio of the signal photon counts divided by the noise photon counts. The background light was varied to four different levels that were approximately equal for each configuration. The reason that the data points do not have the same SNR for each configuration is because the laser power levels could not be exactly matched and also by adding channels the amount of noise is increased linearly with the number of channels. A significant reduction of the BER is shown for the two-channel coincidence compared to the single channel baseline. The four-channel configuration also shows a significant reduction in BER from the baseline but the improvement from the two-channel case was not as significant.

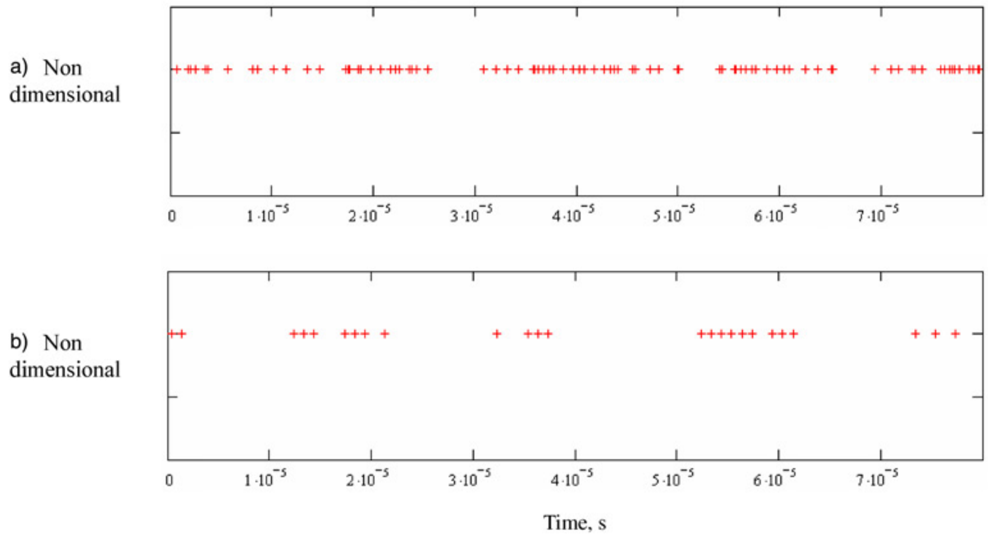


**Fig. 5 A comparison of receiver counts for a) single photon detection events (+symbol) as a function of time for the single channel baseline; and b) photon coincidence detections (+symbol) as a function of time for the two-channel configuration. The bottom axis for both of these graphs is in units of seconds.**

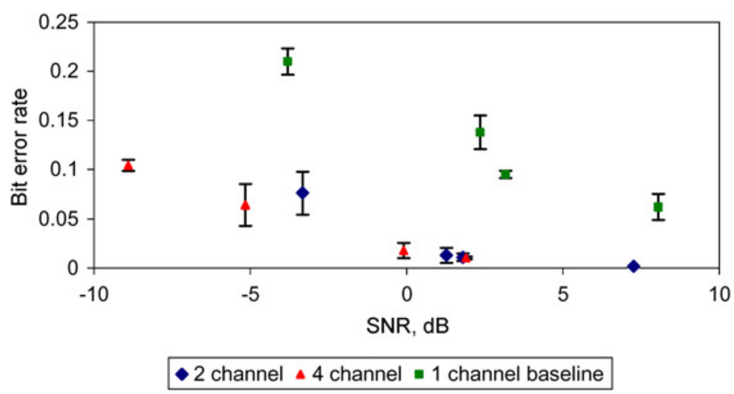


**Fig. 6 Comparison of single channel photon counting communication to time coincident photon counting communication. This graph directly compares the measured SNR to BER. The variation in error for each point was caused by varying amounts of beam wander. The beam wander would change because there was a large temperature difference along the hallway where the experiment was conducted that was made worse by the building heating system turning on periodically during the experiment. The error bars are one-sigma on each side of the data point.**

To more fairly evaluate this data a second graph has been generated in Fig. 7 where the SNR is calculated in a way that compensates for the deflated SNR that results from inflated noise levels caused by additional channels. Here the signal is still the sum of the signal photons from each channel. The noise, however, is now calculated as the average number of noise photons per channel, rather than the sum of the noise photons from all channels. In Fig. 7 we see that again a significant improvement comes from using the two-channel photon coincidence as opposed to a single channel photon counting system. A 5 to 7 db improvement has been measured in these tests. The data however does not show an improvement of the four-channel system over the two-channel system. In this case the four-channel system would probably have to be coded with multiple bits, as in Table 2, for a given bit period to see an improvement.

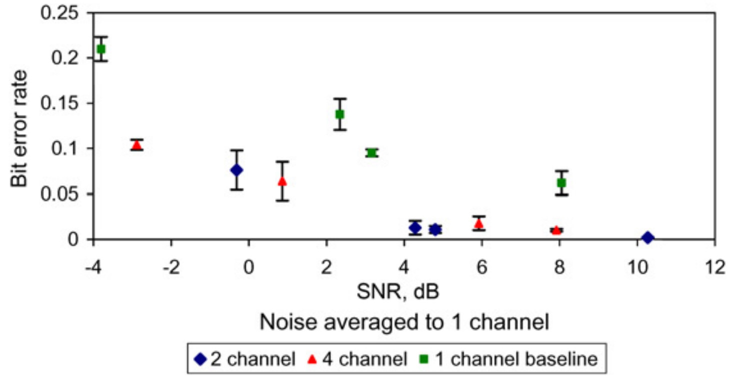


**Fig. 7 In this graph the SNR has been calculated with the signal summed for all of the channels used in a particular configuration. The noise, however, was calculated as an average for a single channel. The error bars are one-sigma on each side of the data point.**

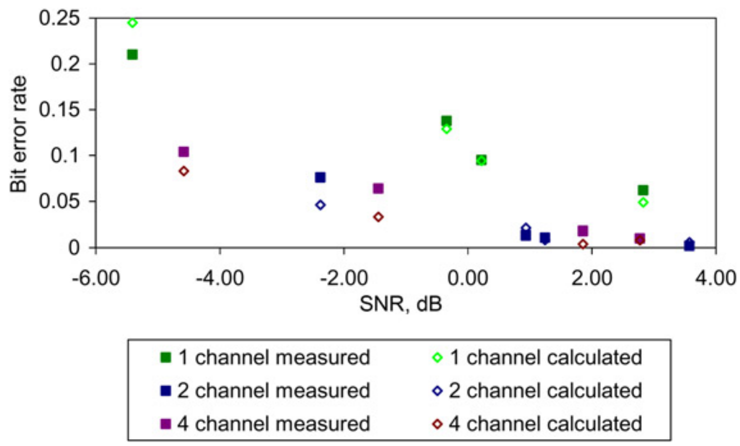


**Fig. 8 In this graph a comparison of the expected BER calculated from the BER equations and the measured BER is shown. In this case the bias caused by the laser not completely turning off has been compensated by counting the laser photon counts outside of the pulses in with the noise for that detector.**

A comparison of the expected BER calculated from the equations presented earlier and the measured BER is shown in Fig. 8. In this comparison it should be noted that the bias caused by the laser not completely turning off has been compensated by counting the laser photon counts outside of the pulses with the noise for that detector. These compensated signal and noise photon counts for each individual detector were then used, along with the BER equations, to obtain the calculated BER for each condition. In this figure it can be seen that there is fairly good agreement between the calculated BER and the measured BER. Beam wander is probably the main contributor to the discrepancies between the measured BER and the calculated BER.

The experiments performed here demonstrate the potential for this technique for a very low power system. The BERs achieved are not those that would be required for a planetary mission. In that case the BER would have to be in the range of $10^{-7}$. While that has not been demonstrated with this experimental system there is significant potential to reach this level. Improvements in the transmitter and receiver to reduce the source pulse time to 1 ns and the coincidence time to 1 ns would significantly improve the BER. Also increasing the number of pulses to 15 or 20 would significantly improve the BER. Also, it is possible that pulse position modulation could be used to further decrease the power per bit and forward error. Correction coding could likewise improve the BER. The technique has demonstrated significant noise immunity in the presence of background noise, and with further system refinement and the inclusion of standard coding and modulation techniques, it has the potential to enable free space communication for miniature sensor stations.

## IV. Conclusion

In this paper a new low power optical communication system has been presented. In contrast to traditional photon counting, the system is made significantly immune to background noise by only counting photon coincidences. Experiments conducted with this system have shown that a signal of just 360 pW can have an effective range of 70 m even in the presence of ambient light levels similar to what can be expected outdoors. The experiment, while not optimized, has demonstrated low error communication at significantly lower signal-to-noise ratios than is possible with traditional photon counting. Previously this type of communication method has been accomplished using non linear systems to generate quantum entangled photons. The system presented here has been developed because it can more readily use the smallest high-efficiency sources that tend to have low total power levels. With sources such as these, the transmitter electrical energy can be as low as a billionth of a watt, which would overcome a significant hurdle for miniature planetary sensor platforms.

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