Optical wireless communications with low voltage self-powered sensor motes

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Optical wireless channels that use modulated retro-reflectors can provide low-data rate communications to self-powered 'smart-dust' motes. The retro-reflectors are illuminated using a base station that incorporates diffractive beamsteering to direct radiation onto the motes, and these return the radiation to an imaging receiver within the base station. The motes consist of a photodiode to provide power, a novel logarithmic receiver to receive data from the base station, and a modulating retro-reflector to send information from the mote to the base station.
Several of the components elements of this system have been implemented and tested. In this paper we report a logarithmic receiver that can be self powered by the source communicating with it, and a retro-reflecting LC modulator component that operates at 30b/s when driven at 0.7V. In addition an overall system model, together with the challenges for future work are presented.
Keywords: Optoelectronic systems, optical wireless communications, retro-reflectors, sensor networks

1. Introduction

A key challenge for sensor networks is to create sensor 'motes' that have low power consumption, and hence a long lifetime. Sensors that 'scavenge' energy from their environment are attractive for this reason, but these must operate at very low power levels to be sustainable. Most sensor networks use RF communications to transmit information, and this can require substantial amounts of energy for each bit transmitted compared with processing information[1]. This is both due to the complex circuitry required to create the signals, and the low directivity of the RF antennas typically used in such applications, leading to most of the transmitted power being wasted.
Optical channels, however, can be very highly directive, so that path loss can be minimized if transmitter and receiver ends of the link can be aligned. If the sensor uses a retro-reflector rather than an optical source, then the only energy required for communications from the sensor is to modulate the retro-reflector. The modulated beam is then returned to the source creating a sensor-source link. The link from source to sensor can be made by modulating the source, and this radiation (along with any ambient illumination there might be) can be used to power the sensor. The University of Oxford is involved in a UK government funded project that aims to demonstrate such a system[2]. In this paper we report results from the key communications components: a novel logarithmic receiver, and a low-voltage retro-reflecting modulator. Data from these is used to infer actual system performance.

1.1. System Overview

Figure 1 shows the system concept. A base station (BS) sits above a coverage area, and illuminates a Smart Dust Mote (SDM). This is achieved using a liquid crystal spatial light modulator that displays a hologram[3] that steers light to the desired position. The hologram is calculated to direct light to one or a number of sensor nodes simultaneously and also to add any additional phase to the beam that may be required to correct for system aberrations. Beams from the BS illuminate individual sensors, and are retro-reflected back to it and are then detected by an imaging receiver. Each pixel of the receiver corresponds to a region of the angular space addressed by the BS, and initially it is assumed there is only one sensor detected on a single pixel.
The initial mode of operation envisaged is that the SLM steers a beam of light to each node in turn. Illumination by the interrogating beam powers the SDM, and a message can be sent from the BS to the communications receiver by modulating the illuminating beam. Messages can be sent from the SDM to the BS by using the retro-reflecting modulator on the mote.

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A full SDM would have memory, processing and the ability to sense different aspects of the environment, but in this case the communications is of interest, and the component consists of the power diodes, communications receiver and retro-reflecting modulator.

A demonstration system is currently under construction, and the key components are described in the following sections.

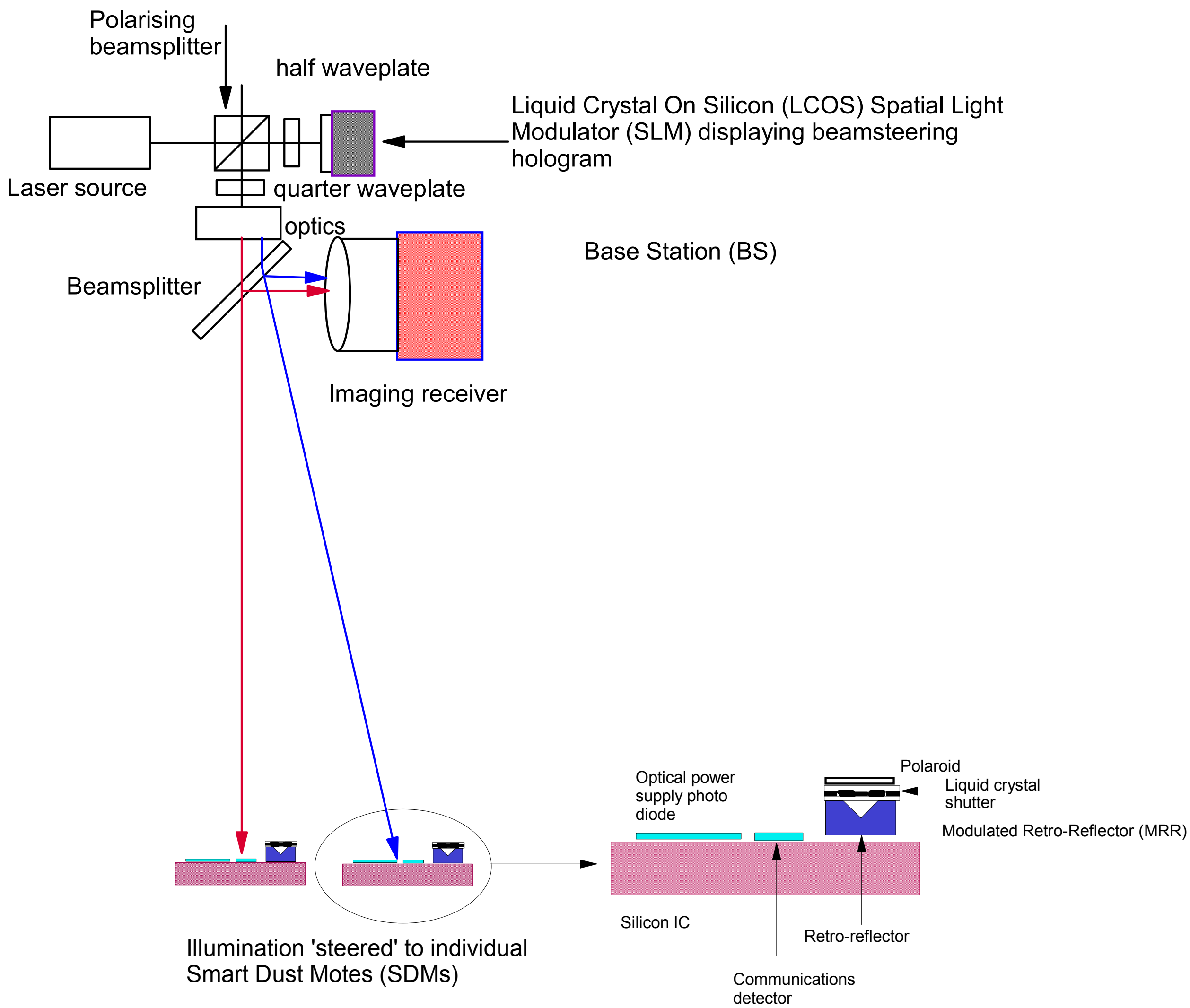


Figure 1. 'Smart Dust' network

1.2. Base station

The BS uses a 785nm laser source that can be modulated to provide downlink communications, to power the motes and provide retro-reflector illumination. This illuminates a silicon backplane Liquid Crystal on Silicon (LCOS) device [4] that displays binary phase holograms. These can steer the illuminating beam through a two dimensional angular field of ~3.3x1.65 degrees at this wavelength. Further optics is used to multiply this steering range to the 15x15 degree field of view required by the system.

The LCOS device requires a linear input polarization state that is aligned correctly in order to provide good phase performance. This is achieved by launching a linear state from the laser, and using a polarizing beam cube to address the device. In addition a half-wave plate is required between the device and the cube to fine-tune performance. Depending on the state of the LCOS pixels the reflected components will have rotated polarization, and will therefore be directed out of the other port of the beamsplitter. This is the desired component, containing the phase modulated wavefront. A quarter-wave plate is then used to circularize the polarization, and the resulting light passes through optics that magnifies the angular range of the beamsteering and focuses the beam at the required range. The circularly polarized beam then passes through a non-polarizing beamsplitter and propagates to the mote where it is intensity modulated by the retro-reflector. Using a circularly polarized illuminating beam ensures that the orientation of the SDM does not affect the returned modulation.

The resulting linearly polarized beam then passes back to the BS but is diverted to the imaging receiver by the beamsplitter. A lens focuses the nominally collimated return beam onto a CMOS camera. Subsequent signal processing is used to recover the modulation from the returned optical signal.

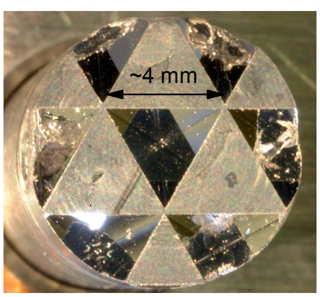
1.3. Smart-Dust Mote (SDM)

Figure 1 also shows a conceptual diagram of the smart dust mote. This consists of a retro-reflecting modulator, a communications receiver and a power photodiode that supplies energy to operate the system. These components are discussed below.

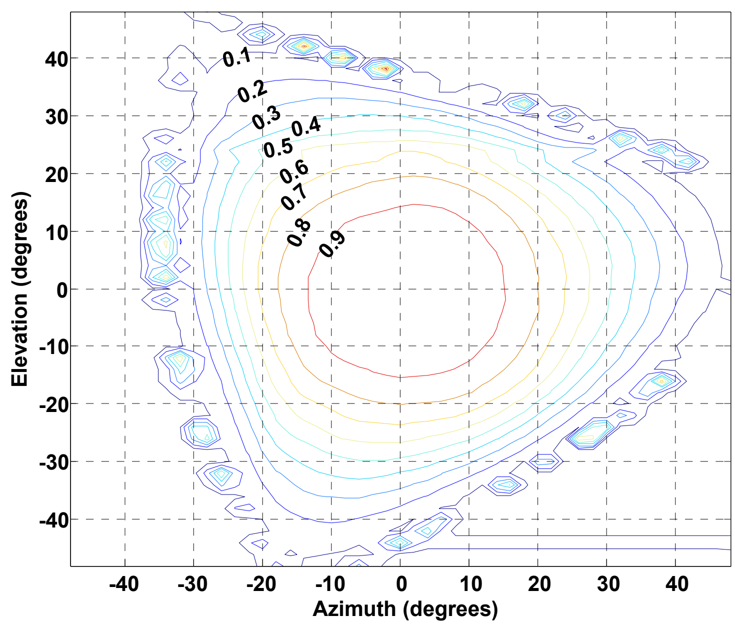
1.3.1. Retro-reflecting modulator

1.3.1.1. Retro-reflector

The use of both cats-eye [5] and corner-cube[5] retro-reflectors was considered for the demonstration system, and measurements were made on various types of commercially available devices. The final device chosen was a modified plastic moulded part, which allowed a corner-cube approximately 4mm in diameter to be extracted from it. Figure 2 (a) shows the retro-reflector itself and Figure 2(b) shows a plot of the reflectivity of the device, with varying angles of incidence. This plot is normalized to the on-axis (boresight) value, and is taken using a visible light (633nm) illuminating beam that 'overfills' the device. The theoretical maximum boresight reflectivity for an overfilled device of this type is 66%, and it is thought that device performance is close to this value. Calibrated measurements to verify this will be undertaken in the future.



(a)



(b)

Figure 2. (a) Retro-reflector .(b) Measured angular response.

1.3.2. Liquid crystal shutter

The liquid crystal shutter must operate at voltages compatible with those produced by photodiodes fabricated in the silicon process used for the power source of the integrated circuit. A survey of the available literature indicated that drive voltages of 0.7-1.0V might be available, so an initial specification for the device was to operate at 1V with sufficient modulation at 100b/s. A Hybrid Aligned Nematic (HAN) cell geometry has the potential to provide low voltage switching required if thin (~1μm) cells are used. Liquid Crystal (LC) materials with low ionic content are preferred for this application as they can be operated using a unipolar switching voltage, which is suited to the 'single-rail' power supply from a single photodiode. A number of suitable liquid crystal cells of were fabricated and tested by driving using Manchester coded data at different bit-rates and voltages. Measurement of the actual power photodiodes showed that drive voltages of 0.7V were available, rather than the 1V initially expected, so tests were made at these levels.

Response measurements were made on a prototype retro-reflecting modulator, consisting of a polarizer, liquid crystal cell and retro-reflector. This was addressed with a laser, and the resulting retro-reflected signal measured with a photodetector. The cell is modulated with the data waveform, and initially the polarizer, cell and retro-reflector are rotated to give maximum modulation.

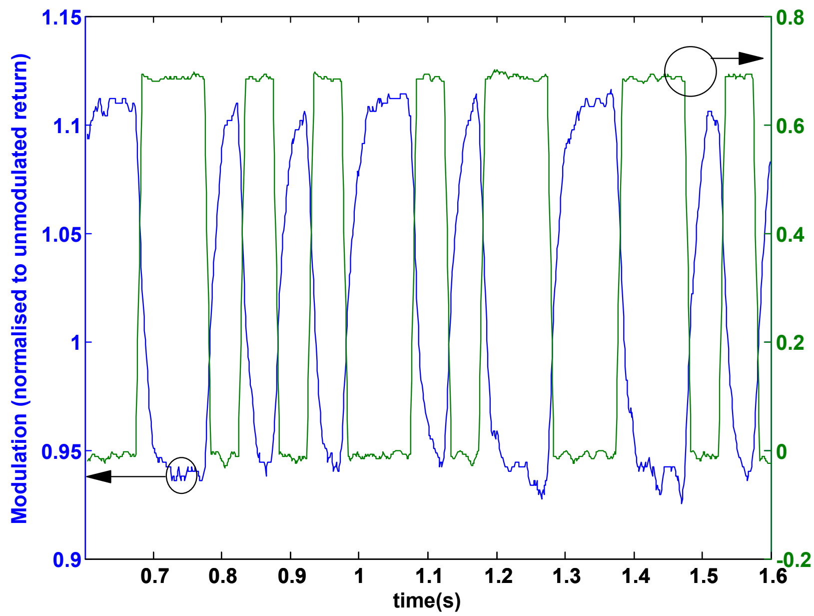


Figure 3.Response of low ionic LC material operating at 10b/s Manchester coded

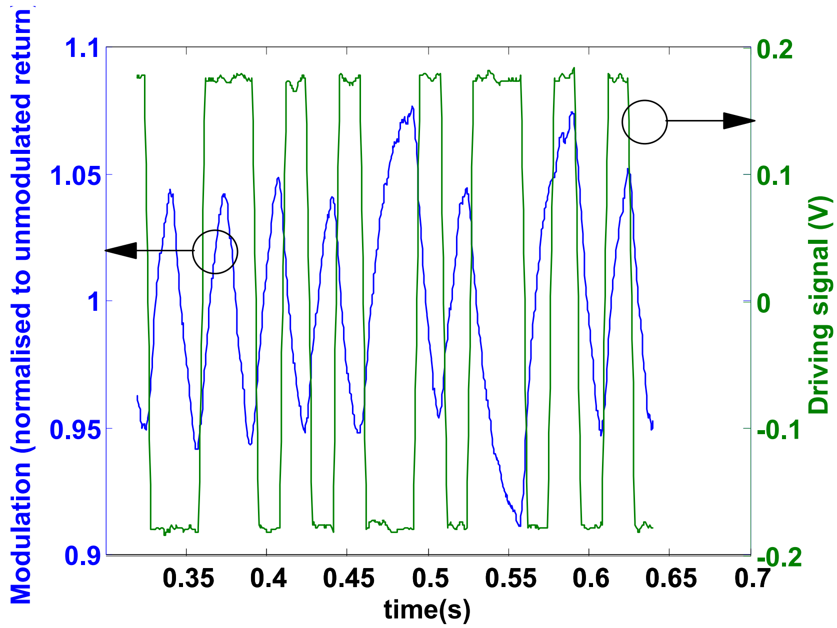


Figure 4. Response of low ionic LC material operating at 30b/s Manchester coded

Figure 3 and Figure 4 show the optical response of the low ionic materials operating at 10b/s and 30b/s respectively when driven at 0.7V. The graphs show the optical modulation (defined as the received power/received power with no electrical drive signal applied to the LC) with the polarizer rotated for maximum modulation depth. For the 10b/s the depth of modulation is approximately 0.15, and for 30b/s the bandwidth of the LC is being exceeded, causing wider variation in this value- between 0.1 and 0.15. At present the speed of the device is lower than the desired 100 b/s, largely due to the lower driving voltage available (0.7 rather than 1.0 V) and in the longer term work to improve this response will be undertaken.

1.3.3. Silicon CMOS circuits.

The SDM contains a power photodiode which provides the current used by the circuitry. This is generated both by the illumination from the interrogating beam and also any ambient illumination that there may be. Various types of junction were fabricated in a 0.25µm CMOS twin-well process, in order to ascertain what operating voltages were available. For the best photodiodes quantum efficiencies of 11.8% were obtained at 785nm.

The photocurrent from the power diodes is used to power the communications receiver. Figure 5 shows a block diagram of this element.

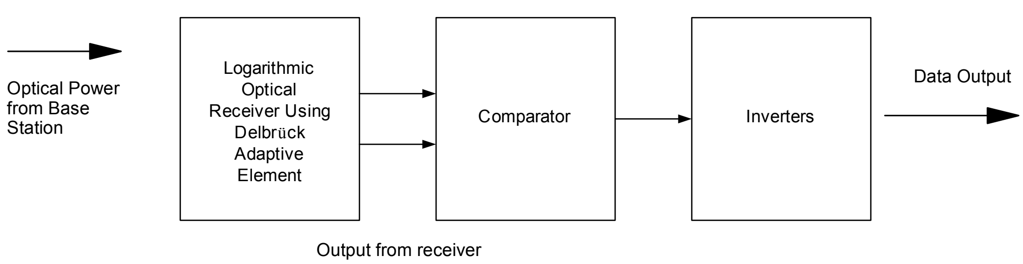
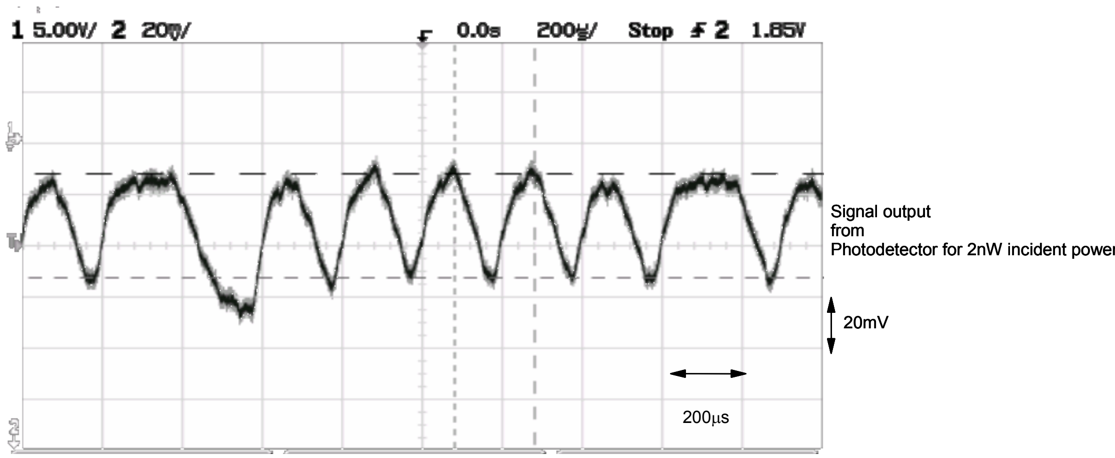
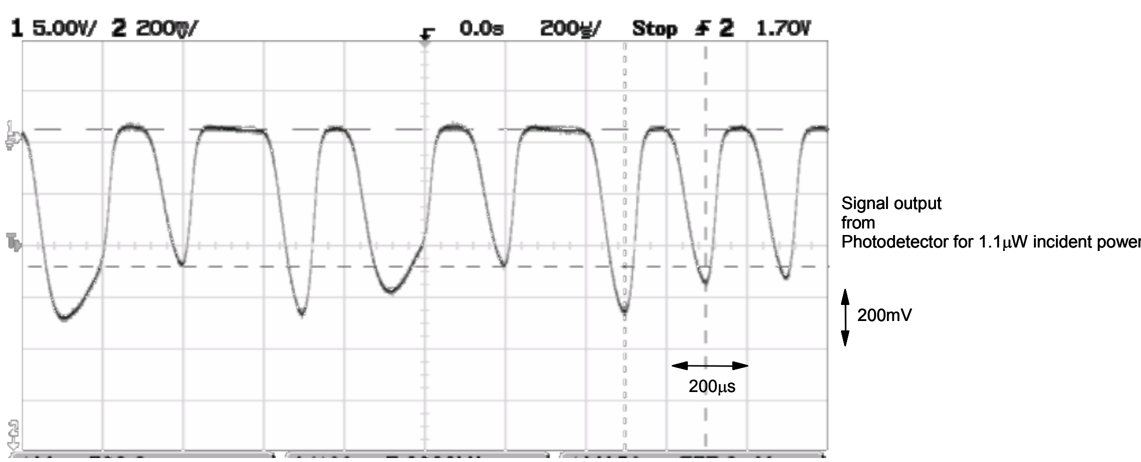


Figure 5. Block diagram of receiver

The front end consists of a logarithmic receiver that, to a first order approximation, operates on the modulation depth of the received signal, rather than the absolute modulation. The circuit uses a Delbruck adaptive element [6] to achieve this function. Tests were undertaken to evaluate the performance of the receiver. The detector was illuminated with 785nm radiation that has Manchester modulation imposed on it. The depth of the modulation (using a similar definition as previously) is from 1.4 to 0.6 of the mean transmitted power. In practice the receiver would be powered from the power photodiode, but for this test a voltage supply of similar voltage was used. The available voltage varies with incident optical power, so that at longer distances from the BS, where the illumination intensity is lower the supply voltage is reduced. Figure 6 (a) shows the results of a test with a 0.5V supply, corresponding to a range of approximately 30m, the nominal maximum range. In this case the power incident on the receiver photodiode is 2nW. The figure shows the signal received output from the adaptive element. A similar test was carried out at intermediate and short ranges. The short range test used an illumination of 1.075 μW, with an operating voltage of 0.7 V, corresponding to a range of 2m. Figure 6(b) shows the results from the element for this power level. In this case the amplitude has increased from approximately 40mV to 400mV, so the circuit has compressed the three orders of magnitude difference in input signal to one order of magnitude in the output. Figure 7 shows a typical output from the comparator circuits (for the case of maximum range) showing correct thresholding of the data.



(a)



(b)

Figure 6. (a) Receiver operation with 2nW incident power. (b) Receiver operation with 1.1 μW incident power

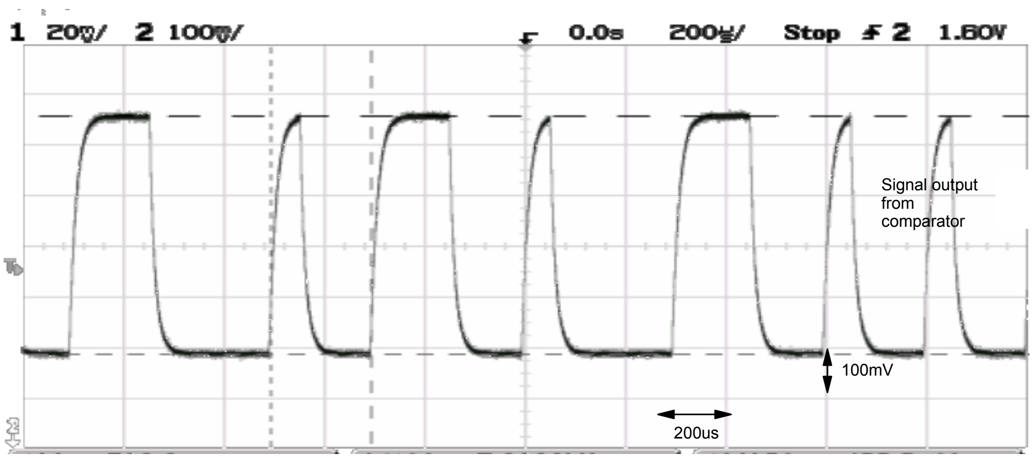


Figure 7. Typical output from receiver inverters

1.4. Overall system operation

Table 1 shows the overall system specification, using measured values where available.
The range of the system has two constraints. The communications link must return sufficient power to the BS to operate the link at the required BER, and the illumination from the downlink must provide sufficient power to operate the SDM. Measurements of the prototype receiver, together with the requirements of other parts of the mote indicate that 20nA of photocurrent is required to operate the SDM. Figure 8 shows the photocurrent that could be provided by an interrogating beam with the characteristics shown in table 1. This indicates an approximately 30m range is possible, and at this range it can be seen from the figure that approximately 3nW of optical power is incident on the communications detector, ensuring correct operation of the downlink.
Detection of the data transmitted by the mote is achieved by a CMOS camera. This integrates the received signals at each pixel for a specified period of time, and converts the stored charge into an 8 bit number. The signal consists of a small modulation superimposed on a large average component, so subsequent processing will be required to obtain the modulated data. This will be undertaken using a framegrabber linked to a fast control PC.
Figure 9 shows the estimated modulated power received at the camera vs. link range. The random noise of the camera is <0.5bits, and this, together with the modulated power can be used to estimate the BER. A Q value of approximately 6 is required for a BER of 10^{-9} and this is achieved if the modulated power is converted to a number greater than 3 bits (so that this number divided by the random noise exceeds 6). For the power levels shown in the figure a BER of 10^{-9} can be achieved at range of 100m by integrating the received signal for approximately 250µs, showing that uplink performance does not limit overall system range (which is limited to 30m by power requirements).
The constraint on modulation depth is therefore that it should exceed 3/256 or approximately 1% for the system to operate at the required BER. If this is not possible the camera will saturate before the difference in received powers between 'on' and 'off' levels is equal to the required 3 bits. There is a further constraint on the minimum and maximum ranges for system operation. For a maximum range of 30m and a minimum range of 1m the incident power varies by almost three orders of magnitude, so steps must be taken not to saturate the camera.
This can be achieved by power control at the transmitter, or changing the time over which power is integrated by the pixels in order to prevent saturation at close ranges. Both strategies should be possible for the case where one SDM is addressed in turn by the BS, and these will be investigated in future work.

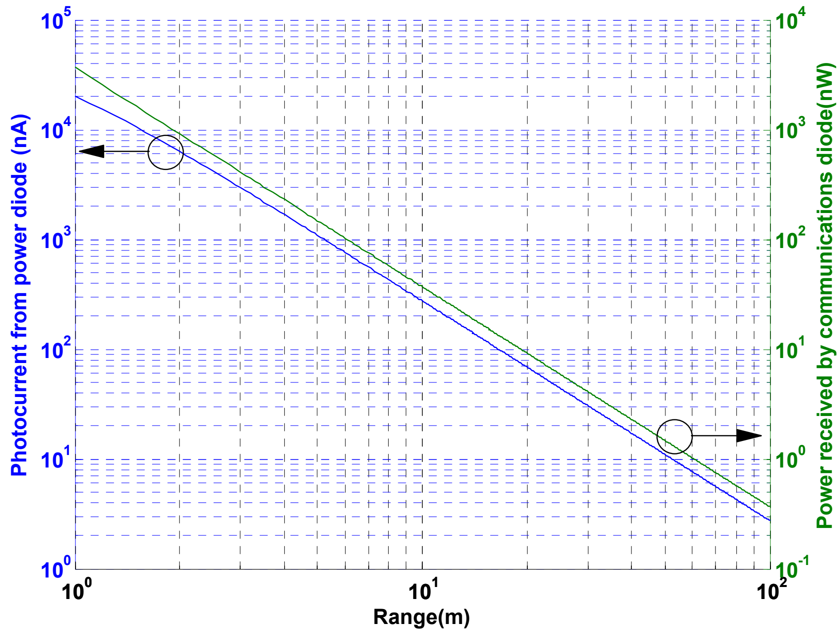


Figure 8. Power incident on communications detector and available photocurrent

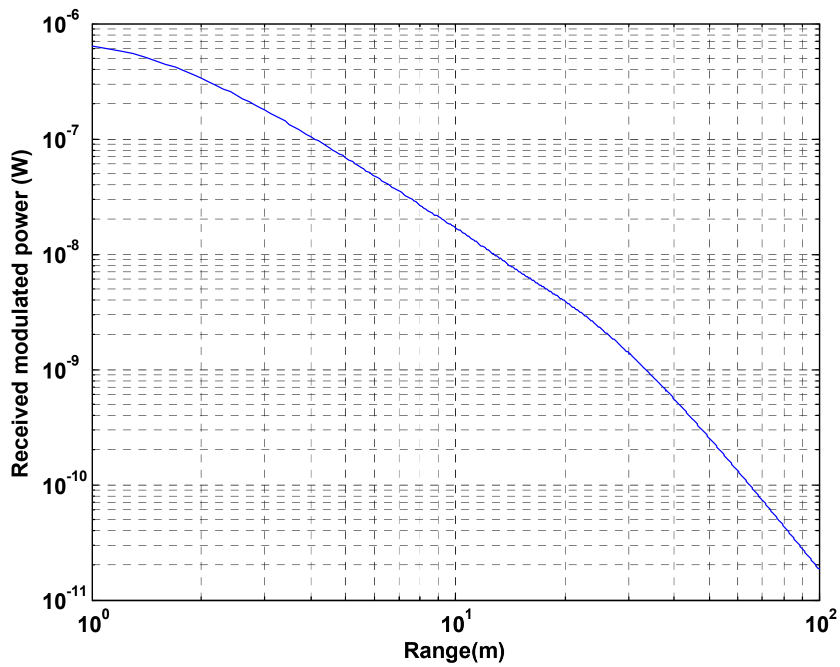


Figure 9. Link loss vs range

Transmitter	Initial values	Current values	**Uplink**	Initial	Current values
Source power	0.5mW	0.5mW	**Retro-reflecting transceiver(RRT)**		
Wavelength	850nm	785nm (due to improved diode quantum efficiency)	Data rate	100b/s	30 b/s (reduced due to lower available voltage)
System Field of View	15deg (half angle)	15deg (half angle)	Modulation scheme	Manchester	Manchester
Transmitter beam	High order lambertian with half angle 0.5mrad	High order lambertian with half angle 0.5mrad	Modulator	Hybrid aligned nematic LC	Hybrid aligned nematic LC
			Modulator diameter	1mm	1mm square
Downlink			Contrast ratio	1.2:1	1.1:1
Data rate	10kb/s	5kb/s (due to reduced working voltage)	On transmission	100%	Not measured
Modulation scheme	Manchester	Manchester	Retro-reflector	Corner-cube	Corner-cube
Receiver			Reflectivity at edge of coverage area	0.41	Measurements indicate 0.41 conservative value
Design	Logarithmic pixel	Logarithmic pixel	BS imaging receiver		
Receiver area	7500μm^2	7500μm^2	Optical collection lens	1.6cm diameter	
Detector quantum efficiency	0.1	0.118 (measured)	Detector	1024x1024 pixel 8 bit CMOS camera	
Detector responsivity		0.0747A/W	Quantum efficiency	0.12	
Minimum received average photocurrent (at 30m range)	~20nA	Power supply current	Exposure time	Variable	
Modulation depth of downlink beam (Max-Min)/(Max+Min)	0.2	0.4 (increased to improve signal reception)	Camera noise	0.5LSB	
			Receiver system transmission factor (from beamsplitter-camera detector)	0.27	

Table 1. Communications Link design parameters

1.5. Conclusions and future work

Successful wireless sensor networks require low-power consumption nodes with long lifetimes, and for these reasons self-powered devices are attractive. A communications receiver that consumes 10nA at 0.5V has successfully been fabricated, as well as the power diodes necessary to operate it using the interrogating illumination as a power source. In addition retro-reflecting LC modulators that provide sufficient contrast ratio at operating voltages of 0.7V, and bit rates of 30 b/s have been demonstrated. Work to integrate these devices into a self-powered sensor mote is underway.

1.6. Acknowledgements

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1.7. References

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