Optical Wireless Communications for Micro-machines

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ABSTRACT

A key challenge for wireless sensor networks is minimizing the energy required for network nodes to communicate with each other, and this becomes acute for self-powered devices such as 'smart dust'. Optical communications is a potentially attractive solution for such devices. The University of Oxford is currently involved in a project to build optical wireless links to smart dust. Retro-reflectors combined with liquid crystal modulators can be integrated with the micro-machine to create a low power transceiver. When illuminated from a base station a modulated beam is returned, transmitting data. Data from the base station can be transmitted using modulation of the illuminating beam and a receiver at the micro-machine.

In this paper we outline the energy consumption and link budget considerations in the design of such micro-machines, and report preliminary experimental results.

Keywords: Optical Communications, Micro-machines, Retro-reflectors

1. INTRODUCTION

Wireless Sensor Networks (WSN) are of rapidly growing interest, with predictions of billions of nodes being deployed worldwide[1], with items as diverse as electrical appliances, drug packaging and trees having low-powered autonomous nodes that are networked together. A key challenge for these nodes is to communicate with one another in an energy efficient manner, as passing messages is perhaps the single major drain on the finite energy these battery powered nodes have.

At the smallest end of the scale of this work is that on small disposable sensor motes – so called 'smart-dust'[2, 3]. In this case a single mote might be <1mm on a side, and would preferable scavenge power from the environment. In this extreme case implementing efficient communications is extremely challenging.

Working against this aim is the RF Wireless channel. This is essentially a broadcast channel, due to the isotropic gain of the small antennas used by the nodes. Path loss exponents in the range 2.5 to 4 are typical in indoor environments, meaning that large amounts of energy are used to communicate relatively small distances. This can be mitigated by using multi-hop techniques, but this leads to more complicated routing strategies[4]. In addition RF transceiver power consumption is high, due to the IF and baseband processing and the generally complex nature of the transceiver.

Free space optical communications is a potentially attractive alternative to this, largely due to the ability to create highly directed channels using small 'optical antenna' such as lenses or mirrors. These can have low, or even zero path loss, and can therefore create highly efficient communications channels.

There are several challenges that must be addressed; there must be a Line Of Sight (LOS) between the terminals, and a source of optical radiation available to each sensor mote. The LOS problem is addressed by geometry, and the large excess number of low-cost motes that there might be, so that LOS exists to a sufficient number of sensors to provide the required coverage density. There are several alternatives to providing the radiation; a source might be integrated with the dust mote, but this is complex, and the energy required may not be available in very low-power devices. Modulated Retro-reflectors (MRRs) are an attractive alternative to this as the sensor mote does not require a source of light. Figure 1 shows a schematic of such a communications link.

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Free-Space Laser Communications VI, edited by Arun K. Majumdar, Christopher C. Davis,
Proc. of SPIE Vol. 6304, 63041A, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.680780

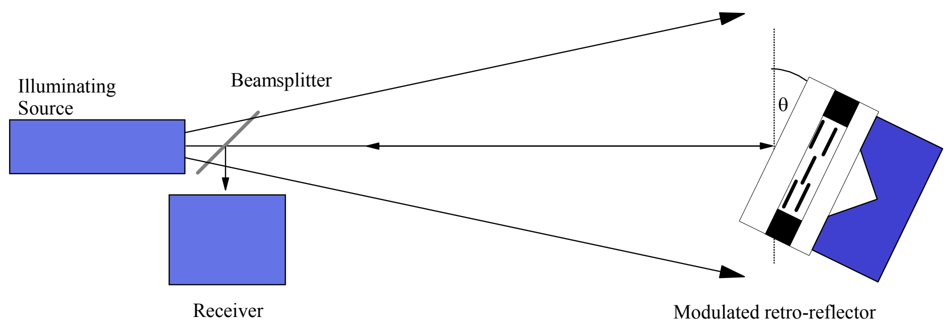

Figure 1. Retro-reflecting data link

A source illuminates the MRR, which returns the radiation to its source due to the action of the retro-reflector. A beamsplitter allows the returned radiation to be directed toward an optical receiver. Modulating the return signal, using a shutter or some means to disturb the reflection allows data to be transmitted from MRR to the reader, and modulating the illuminating beam allows data transmission from the reader to a receiver on the MRR.

A number of links of this type have been reported; in [5] and [6] reflectors using semiconductor shutters have been demonstrated, and these have been used in various transmission experiments[7-10]. Different retro-reflector designs, including cats-eye[11], corner cube[6] and ball-lens[12] are all available, and each have their own advantages and disadvantages.

2. SYSTEM OVERVIEW

Figure 2 shows a typical environment in which such machines might operate. A Base Station (BS) communicates with a number of Smart-Dust Motes (SDMs) within its field of view simultaneously.

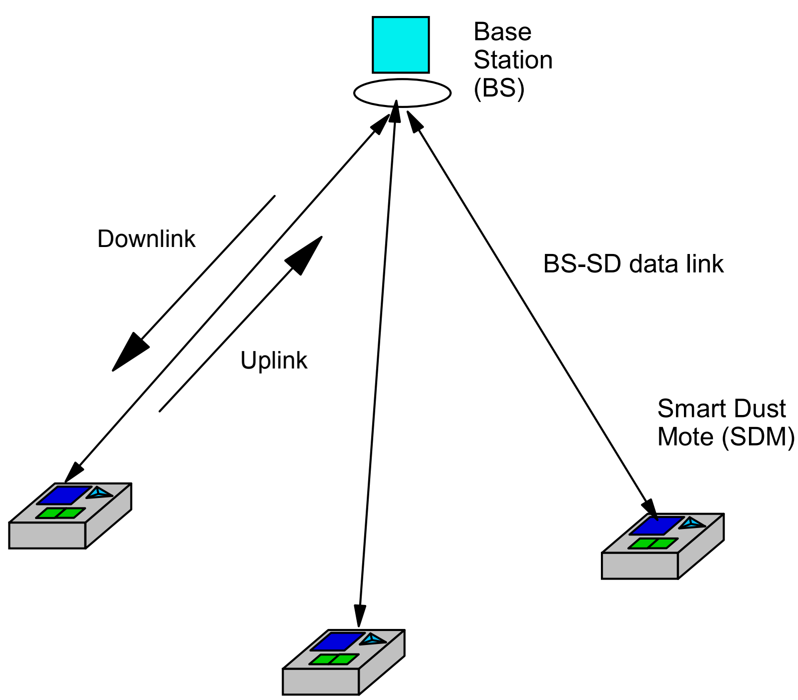

Figure 2. Network of micro-machines

2.1. Base station (BS)

The BS is required to illuminate the SDMs within the coverage area, and to receive the returned signals from those that are active. There are two basic designs of BS that are under consideration, and these are show in Figure 3

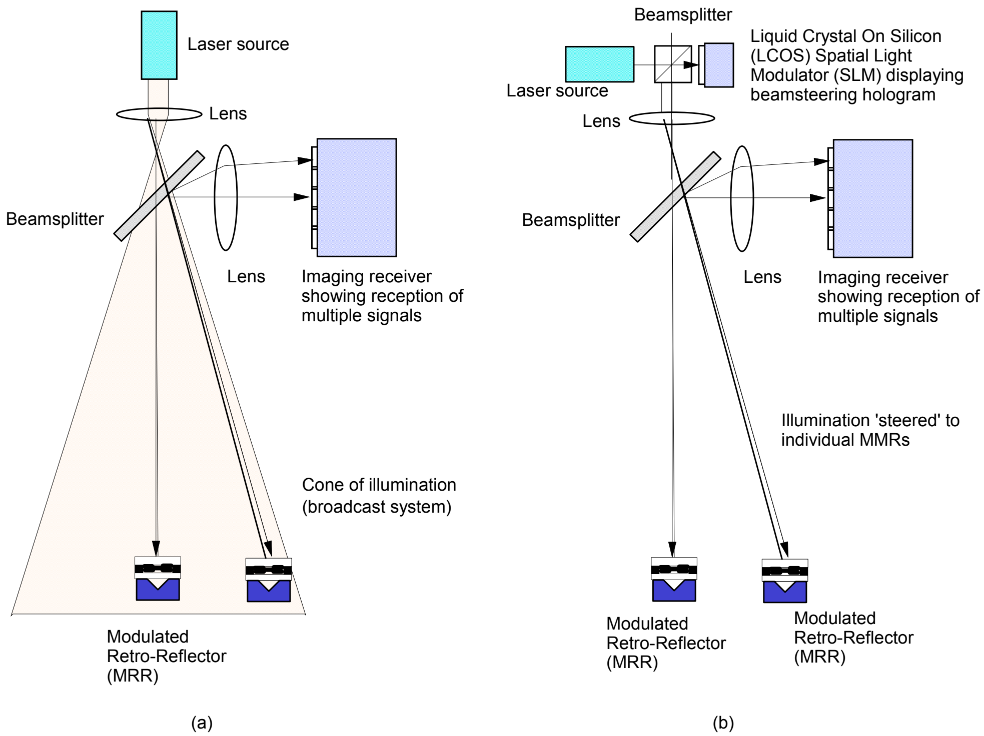

Figure 3. (a) Schematic of broadcast BS. (b) Schematic of beamsteering BS

Figure 3(a) shows a 'broadcast' BS design. In this case a source illuminates the entire coverage area, and light from active MRRs is reflected back to the BS and detected by an imaging receiver[13]. This allows multiple signals to be detected simultaneously. At the low data rates considered here a commercial CMOS camera is attractive for this purpose, as it offers sufficiently high frame rates and good sensitivity. The data can then be recovered in real time using subsequent processing. The disadvantage of the broadcast design is that most of the illuminating power is wasted, limiting the range of the links, and the illumination intensity available to power the SDMs. In Figure 3(b) a BS design that uses beamsteering to direct narrow beams to SDMs is shown. The beamsteering is implemented using a Computer Generated Hologram displayed on a Liquid Crystal Spatial Light Modulator (SLM)[14]. This allows almost arbitrary illumination patterns to be generated, so that multiple SDMs can be addressed. For this system to operate the location of the motes must be known, so that a tracking algorithm is required. Several alternative methods to achieve this are being investigated at present.

2.2. Downlink

Downlink communications are achieved by modulating the illumination source, and detecting the received signal at the Smart-Dust Mote (SDM). For the downlink a single source will be used to address the SDMs and there are two potential modes of operation. In the first the beamsteering transmitter addresses SDMs in turn creating a Space Division Multiple Access (SDMA) scheme, or in the second all SDMs are illuminated and a Time Division Multiple Access (TDMA) scheme is required. At present the downlink is designed to operate at 100 times the uplink data rate, so that 100 nodes can be addressed with the same aggregate data rate as the uplink using the TDMA scheme. This capacity can be increased using a mixture of TDMA between simultaneously addressed nodes and SDMA for sequentially addressed groups of nodes. The downlink also provides power to the SDM, so full modulation of the downlink beam might interrupt the power supply to the nodes or provide unacceptable ripple on the power supply. The minimum acceptable modulation depth (which will depend on the design of the receiver) is under investigation.

2.3. Uplink

The uplink is modulated at a much slower rate than the downlink, and for the two data streams to be separated there must be two modes of BS operation. In the first the BS source is modulated and data is received by the SDM, and in the second the BS illuminates the SDMs continuously, and this radiation is modulated by the MRRs. This modulation is then detected by the imaging receiver.

The imaging receiver has a large number of pixels, each of which is mapped to a small part of the coverage area of the BS, so in the first instance it is assumed there will be a single SDM within the coverage area of one pixel and therefore no contention between uplinks. Access schemes that allow more than one SDM to be present in a single pixel coverage area, causing potential contention between SDMs, are under investigation.

3. SMART DUST MOTE (SDM)

Figure 4 shows a schematic of the SDM. This consists of a receiver to allow communications from BS to SDM (the downlink), a modulated retro-reflector (MRR) in order to provide an uplink. Circuitry is implemented in a custom silicon IC.

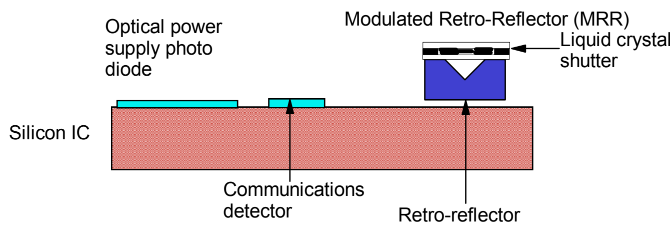

Figure 4. Potential 'smart dust' layout

The silicon IC is a custom designed structure, fabricated using a 0.25 μm UMC twin-well CMOS process available through the Europractice IC service. The first generation device consists of series connected photodiodes to form the power supply, test communications detectors, and test modulator drivers. Data from the measurements will be used in the detailed integrated demonstrator design.

3.1. SDM communications receiver

As the range of the transceiver, and thus the received optical power, can vary substantially a logarithmic response receiver design[15] is used. This responds to the contrast ratio of the optical modulation it receives, rather than the absolute value of signal. In addition the average level of the illumination provides power to the SDM, by illuminating a pair of series connected diodes fabricated on the IC. The average optical power is limited by eye-safety considerations, and the modulation depth is set by receiver performance. As this is CMOS process dependent these parameters will be optimized given test results from the first fabrication run.

3.2. Modulated retro-reflector

Figure 5 shows preliminary layout diagrams for MRR devices using LC modulators. In (a) a cats-eye design is used, with a shutter in the back focal plane of a nominally telecentric lens. This simple design has a limited field of view over which it acts as a retro-reflector, but is potentially very compact and small commercial devices are available. In (b) a design using a Corner-Cube Retro-reflector (CCR) is shown. In this case small devices are difficult to obtain, but a process to build small CCR devices has been developed in the Department of Physics at Oxford, and this will be investigated.

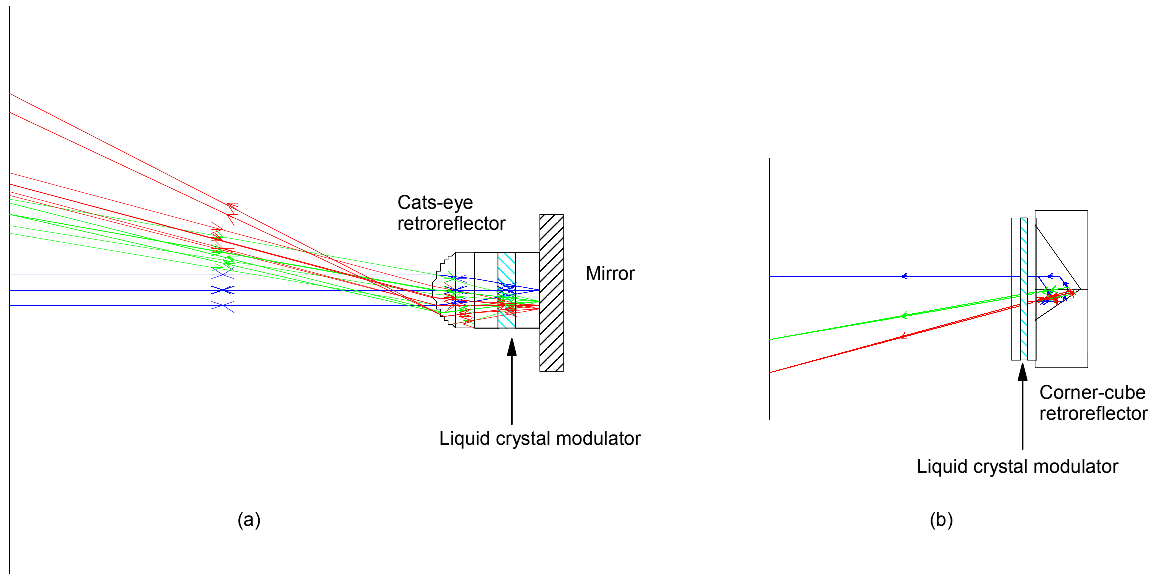

Figure 5. Potential retro-reflecting transceiver designs

3.3. Modulator

There are several alternative modulator materials and structures and it is interesting to compare their performance in terms of switching energy. Switching energy is related to CV^2, if the capacitance of the modulator structure is C and the device requires V volts to switch. In the case of a square drive pulse it is equal to this value, but this dissipation can be reduced using adiabatic driving schemes[16]. However, this measure provides a useful comparison.

Retro-reflectors using Micro-Electrical-Mechanical-Systems (MEMS) have been proposed and demonstrated. Such retro-reflectors are electrostatically activated and require charge pump structures to create the desired voltages. Typical energies for these are 40pJ/bit for a 0.5x0.5mm retro-reflector[17].

Multi-Quantum Well (MQW) modulators have capacitances of approximately 50pF/mm^2 and for a 0.5x0.5mm device would have a switching energy of 300pJ (assuming a 5V switch, which might provide 4dB modulation). MQW retro-reflecting-arrays have been fabricated using a cats-eye retro- optical system [8, 11].

For the application considered here Liquid Crystal (LC) devices offer several advantages; they can operate at low-voltage, and high contrast shutters can be fabricated. As a comparison a 0.5x0.5mm square 1μm thick cell filled with an LC with an average relative permittivity of 10 (corresponding to capacitance of ~90pF/mm^2) and a 1V switching voltage energies of 20pJ/bit might be achieved.

The liquid crystal shutter must provide sufficient modulation to transmit data, but operate at low voltage (typically less than 1V). This is in marked contrast to that typically used for displays, so work to maximize the cell performance (in terms of its contrast ratio and average transmission) is required. The cell under consideration is a Hybrid Aligned Nematic (HAN) Cell (filled with a nematic LC). In hybrid alignment the long LC molecules are aligned parallel with one surface of the cell and normal to the other. This leads to a low 'soft' switching threshold. Figure 6 shows a simulation of the transmission against time for a cell filled with a nematic LC, with a varying LC layer thickness when a 1V step is applied. From the graphs it can be seen there is an optimum thickness of approximately 0.9μm, where the maximum optical response is obtained. At such low drive voltages the LC may not have time to fully respond, so Manchester coded data is used to drive the device. This code contains 'balanced' bits so the LC is driven into both states equally, compared with Non-Return to Zero (NRZ) where a long stream of either 'zero' or 'one' data bits may lead to a larger response as the driving voltage is present for longer. Figure 7 shows a preliminary simulation of the response of such a cell to a Manchester coded data stream, showing that good contrast and modulation should be available.

Work to fabricate such cells is underway. For the initial demonstration a 1x1mm cell area has been chosen, and preliminary results have been obtained that show the necessary low voltage threshold. Further work is required to fully characterize these devices.

In order to further reduce the switching energy there are several strategies that can be used in conjunction with one another. In adiabatic switching the irrecoverable energy that is dissipated by current flow through any charging impedance is minimized by charging the modulator with a ramp rather than a step voltage[16]. This principle might be applied to modulators; further if a multilevel coding scheme were used this would tend to minimize the average voltage change on the device between bits, further reducing energy dissipation and increasing the number of bits per information symbol. This is an area for future investigation.

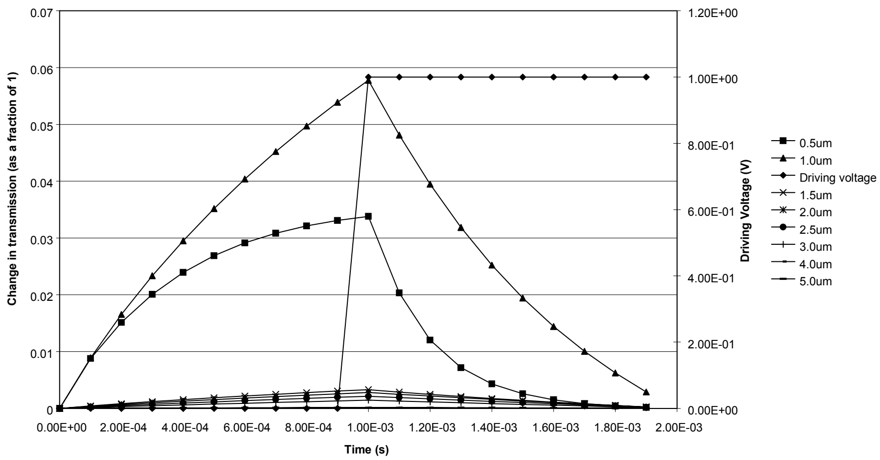

Figure 6. Simulated optical response for different LC cell thicknesses

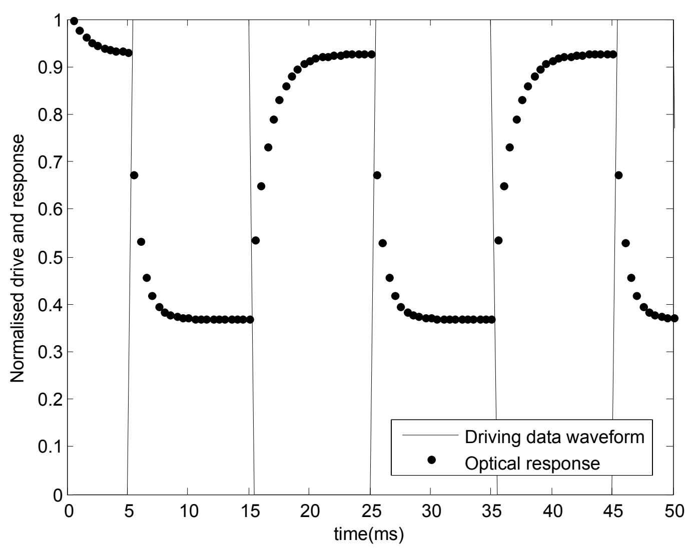

Figure 7. Simulation of cell transmission with 100b/s Manchester data modulation

4. LINK SIMULATION

The correct operation of the SDM is constrained by the link loss of the retro-reflecting up link, the illumination intensity on the power photodiode, and the operation of the downlink. A model of the uplink and downlink were implemented in order to verify the range available.

It is assumed the transmitter illuminates an individual RRT with a beam of ~8x the diffraction limited diameter of a beam that illuminates the SLM device (13mm in this example). This provides power to operate the SDM, and a source of radiation for the uplink. The light passes through the LC modulator, the retro-reflector and through the LC once more. The beam then propagates back to an imaging receiver[13]. The divergence of the returned beam is assumed to be diffraction limited and controlled by the diameter of the LC modulator. Table 1 shows the major link parameters.

Figure 8 (a) shows the link loss (in dB) of the link and (b) the illumination intensity at the smart dust mote. For a BER of 10^{-9} a range of approximately 190m is achievable when the link loss is taken into account. Design of the SDM circuitry indicates a supply current of approximately ~20nA is required to operate the downlink receiver and modulate the LC, and it is assumed this is provided by a power diode with a quantum efficiency of 10%. This limits the range to approximately 30m. It should be noted that extra energy may be available from the environment, and the quantum efficiency is likely to be closer to 20%, thus allowing power for extra information processing.

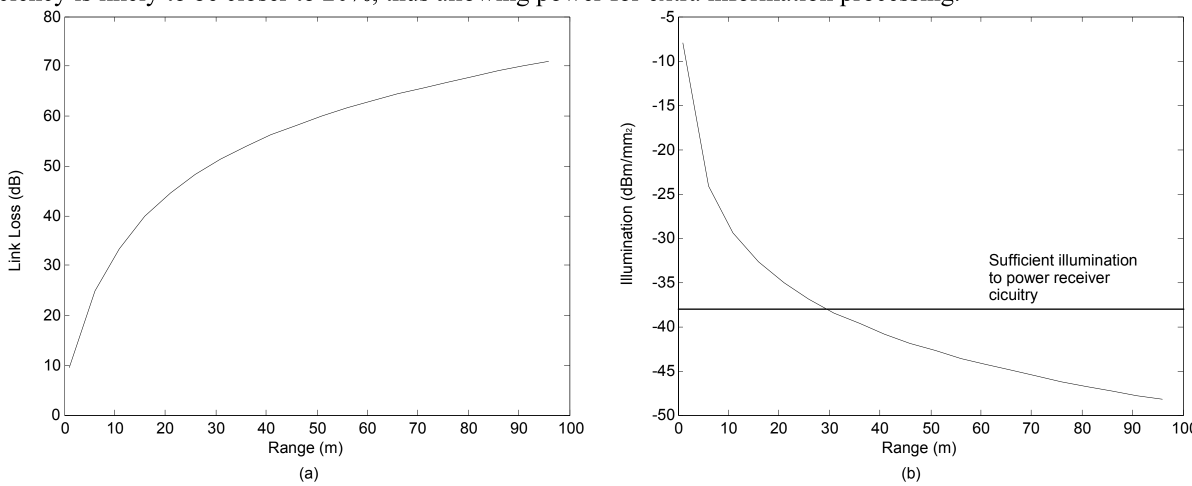

Figure 8. (a) Link budget for uplink. (b) Illumination (/mm^2) on smart dust mote

Transmitter		**Uplink**	
Source power	0.5mW	**Retro-reflecting transceiver(RRT)**	
Wavelength	850nm	Data rate	100b/s
System Field of View	15deg (half angle)	Modulation scheme	Manchester
Transmitter aperture	13mm	Modulator	Hybrid aligned nematic LC
Illumination beam diameter	8.3x diffraction limit of transmitter aperture	Modulator diameter	1mm
Downlink		Contrast ratio	1.2:1
Data rate	10kb/s	On transmission	100%
Modulation scheme	Manchester	Retro-reflector	Corner-cube
Receiver		Reflectivity at edge of coverage area	0.41
Design	Logarithmic pixel	**BS imaging receiver**	
Receiver area	7500μm^2	Optical collection lens	1.6cm diameter
Detector quantum efficiency	0.1	Detector	1024x1024 pixel 12 bit CMOS camera
Minimum received average photocurrent (at 30m range)	~20nA	Quantum efficiency	0.12
Modulation depth of downlink beam (Max-Min)/(Max+Min)	0.2	Exposure time	3ms
		Camera noise	0.5LSB
		Ambient light intensity	40mW/(m^2 Sr nm)
		Optical filter bandwidth	10nm
		Optical system transmission	0.8

Table 1. Link simulation parameters

5. CONCLUSIONS AND FUTURE WORK

Optical wireless communications using modulated retro-reflectors offers the potential for very low power communications to self-powered sensor motes or 'smart dust'. Preliminary results show that low-voltage LC devices can be used to provide the necessary optical modulation and there is sufficient available photocurrent for self powering of the CMOS devices. Work to produce a hybrid demonstrator is underway.

6. ACKNOWLEDGEMENTS

This work is supported by the UK Engineering and Physical Sciences Research Council.

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