Optical wireless networks using self-powered nodes

Dominic C.O'Brien *Member, IEEE*, Jing Jing Liu *Student Member, IEEE*, Grahame E. Faulkner, Vachiramon Pithamiron, Steve Collins *Member, IEEE*, Steve J. Elston, Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ email: dominic.obrien@eng.ox.ac.uk

***Abstract*—A network of ultra-low power consumption communications nodes is presented. A base station illuminates small retro-reflecting nodes with a low-divergence beam of light. This powers the node, and also allows information to be transmitted to it. A modulated retro-reflector on the node then returns information to the base station. Design aspects, and results from the implementation are detailed in the paper.**

Keywords-Free space optical communication, modulated retro-reflector, ultra-low power

I. Introduction

The energy consumed in communicating wirelessly between terminals is becoming increasingly important. There are predictions that the number of small wireless terminals is set to grow dramatically, but there is the competing aim of reducing overall energy consumption. Techniques to scavenge and harvest energy, and to minimise its consumption, are therefore becoming increasingly important. Optical wireless has the potential to provide low-energy communications, as well as energy to power to a terminal. The ability to direct low-divergence beams of light to their intended destination allows energy lost in communications paths to be minimised. In addition simple baseband communications can be used, with information transmitted using intensity modulation with direct detection (IM/DD). The architecture shown in Figure 1 is designed to make use of these potential benefits. A Base Station (BS) is situated above the desired coverage area. It communicates with a number of small terminals, or Smart Dust Motes(SDM)[1]. These SDMs have a pair of photodiodes that provide power, a communications receiver that detects modulation on the downlink beam, and a modulated retro-reflector (MRR) that modulates the beam that illuminates it and returns it to the BS. In this way the SDM has bidirectional communications with the BS if there is a line of sight with it. Additionally the SDM is 'woken up' and powered by the illuminating beam (although in practice it can also use any available ambient light).

Each of the major components, together with experimental results are described in the following sections.

II. Base Station

The BS consists of a holographic beamsteering system that directs beams of light to the SDMs combined with an imaging receiver that detects the light retro-reflected from them. A Computer Generated Hologram (CGH) is used to perform the beamsteering and this is displayed on a Ferroelectric Liquid Crystal Spatial Light Modulator (SLM) (FORTH DIMENSION DISPLAYS SXGA-R3-XD) used in a binary phase mode[2]. Displaying a simple tilted grating on the SLM allows beamsteering over a field of view of several degrees, and additional optics is used to increase this to approximately

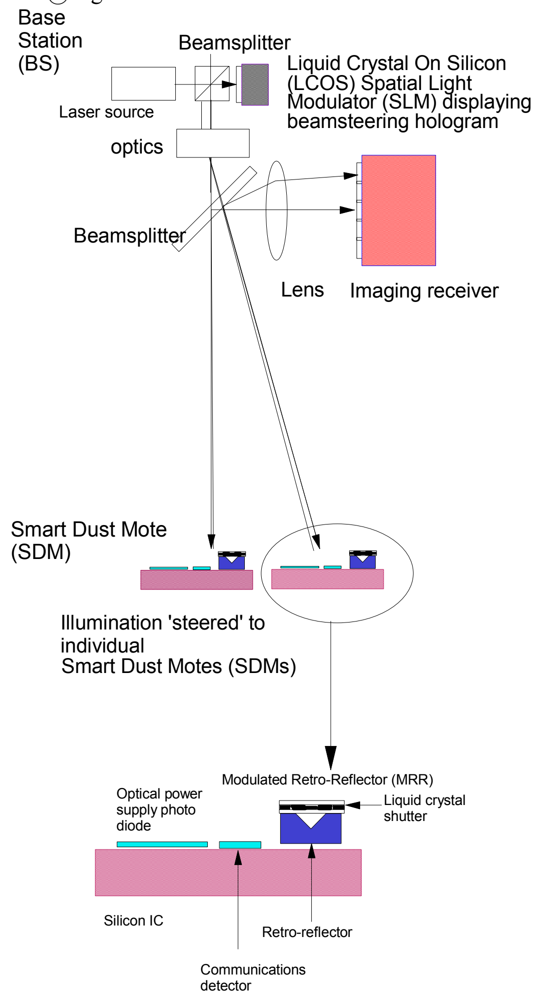

Figure 1. Schematic of optical network

15 degrees. The holographic technique allows beams to be steered to several SDMs simultaneously, and other functions such as focusing power to be incorporated. The resulting beams of light propagate from the BS to the SDMs, and a proportion of the illuminating radiation is returned by each MRR. This light propagates back to the BS and is collected by an imaging receiver. This consists of a collection lens combined with a high frame rate CMOS camera (PHOTON FOCUS MV- D1024E-160-CL), with each pixel on the camera 'mapped' to a small part of the coverage area. The prototype BS operates at 670nm, and is shown in Figure 2.

This work was supported by the UK Engineering and Physical Sciences Research Council (EPSRC).

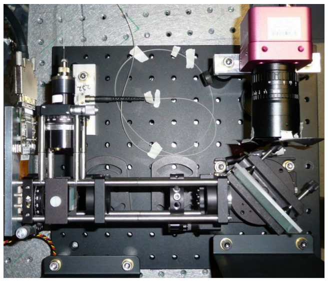

Figure 2. System base station

III. SMART DUST MOTE

Figure 3 shows a the layout of the SDM integrated circuit. This is implemented in a twin-well 0.18um CMOS process offered through the Europractice IC service. Power is provided using a pair of series connected photodiodes, and these can provide 0.6-0.9V for load currents between 1000-10nA depending on the intensity of the illuminating beam from the BS. The overall area of the diode pair is 1.5 mm^2.

Downlink communications is provided by modulating the laser source in the BS. An 8KHz clock is transmitted in addition to a 1kbit/s Manchester coded waveform, using different modulation depths. A logarithmic optical receiver[3] is implemented in the SDM and there is then further decoding to separate the clock and data signal.

Uplink communications is provided using the MRR. The retro-reflector is a modified commercial corner-cube with a side length of several mm. A Liquid Crystal(LC) based intensity modulator (shutter) is positioned in front of the retro-reflector and used to modulate the returned radiation. A very low driving voltage (0.6-0.9V) is available, compared with that usually used for LCs, and custom devices that operate at these levels were fabricated. Thin (3µm gap) cells filled with E7 nematic LC and anti-parallel alignment were found to operate at ~30bits/s with a drive voltage of 0.5V. This corresponds to a switching energy of ~7pJ bit^{-1} mm^{-2}. Figure 4 shows picture of an assembled retro-reflector, in a non-compact geometry. (The active part of the assembly is approximately 1.5mm diameter, in the centre of the mount).

The MRR is driven from control circuitry on the silicon IC that decodes signals from the BS, allowing a 'loopback' test of the node.

IV. OPERATION AND RESULTS

A. Link budget

At the desired range both downlink and uplink must operate correctly, and there must be sufficient illumination to power the SDM. The power emitted by the BS is limited by eye safety considerations (~0.39mW at 670nm for Class 1 operation), and ray tracing simulations indicate correct operation of the SDM at a range of 30m at this power level. This is limited by the need to provide sufficient intensity to power the SDM, rather than the communication functions. Longer range could be achieved by increasing the area of the diodes, or using an optical concentrating element to increase the effective collection area.

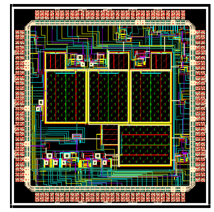

Figure 3. Smart Dust Mote integrated circuit (5x5 mm)

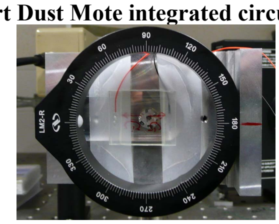

Figure 4. Modulated retro-reflector

B. System operation

Tracking is achieved by using holograms that expand the illuminating beam to cover approximately 1/12th of the coverage area and scanning it until a strong return signal from an MRR is received by the CMOS camera. The location of this return is recorded, and scanning continues until the whole field is covered. These returns provide initial locations, and a simple 'gradient ascent' approach is used to steer low-divergence beam onto each SDM and maximise the received signal.

The uplink and downlink were separately tested. For the uplink the MRR in Figure 4 was used to transmit data, and this was tracked and acquired by the BS at a range of 15m. A ~30bit/s Manchester data stream was transmitted to the imaging receiver. Data is decoded by recording the intensity of the return signal from the MRR in successive frames, and recovering and retiming the resulting data waveform in software. Error free transmission was achieved at this distance, which was limited by the length of test range available. The downlink was tested by illuminating the circuit with an average intensity of 3.5 μWmm^{-2}, similar to that available at range of 30m. Data was transmitted to the SDM, including codes that operate the modulator control circuitry, and these were correctly received and decoded, indicating the downlink operates as planned.

V. DISCUSSION AND CONCLUSIONS

This initial demonstration shows that free-space optical channels offer the ability to minimise path loss and to power low-energy terminals. Work to implement a demonstration network is underway. The simple example shown here does not use energy storage, or ambient light, so there is the potential to harvest additional energy for information processing and sensing functions. This will be the subject of future investigations.

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