Energy scavenging sensors for ultra- low power sensor networks

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ABSTRACT

The 'internet of things' will require very low power wireless communications, preferably using sensors that scavenge power from their environment. Free space optics allows communications over long ranges, with simple transceivers at each end, offering the possibility of low energy consumption. In addition there can be sufficient energy in the communications beam to power simple terminals. In this paper we report experimental results from an architecture that achieves this. A base station that tracks sensors in its coverage area and communicates with them using low divergence optical beams is presented. Sensor nodes use modulated retro-reflectors to communicate with the base station, and the nodes are powered by the illuminating beam. The paper presents design and implementation details, as well as future directions for this work.

Keywords: Energy scavenging, sensor networks, optical communications.

1. INTRODUCTION

The future 'connected world' might have 10-100s of wireless devices for each person, many of them performing sensing functions, such as controlling and monitoring the environment, reducing energy consumption and monitoring human health. Providing these devices, whilst lowering overall energy consumption is extremely challenging.

Strategies to achieve this must include reducing energy consumption due to communications. Broadcast communications, such as that performed by most radio frequency (RF) sensor networks, does not use energy efficiently, and generally the 'cost' to transport one bit is ~0.5nJ/bit and above[1, 2]). Processing information is more energy efficient, leading to the concept of relatively 'smart' low power sensor nodes that can process information locally and transmit data only when required. Reducing the amount of data transmitted also reduces the demands on scarce RF spectrum.

In certain circumstances line of sight optical links can be used to replace RF communications, and this is attractive as such directional links used communications energy efficiently. In addition the simple baseband modulation schemes typically used require very simple circuitry compared with RF. There have been a number of concepts and demonstrations reported[3-8], and retroreflecting links have been considered in some of these as they reduce some of the tracking complexity associated with narrow beam links.

In addition to reducing power consumption energy 'scavenging' allows use of energy such as vibration and heat or light[9], so that additional 'load' of these sensor networks on the energy supply system might be small. In this paper we describe a sensor mote that uses directional optical communications to the sensor, offering power consumption of <20pJ/bit communicated (at the sensor node). This offers the potential to power the system off on-board photodiodes which scavenge energy from either the interrogating beam or ambient light in the environment. A complete description of the system design can be found in [10], and in this paper we report initial results from link demonstrations. In the next section the system architecture is described.

2. SYSTEM DESCRIPTION

2.1 Overview

Figure 1(a) shows the concept. A Base Station (BS) is connected to a number of 'Smart Dust' (SD) nodes using optical links. At the SD light is reflected back to the BS using a retro-reflector. A liquid crystal shutter is used to modulate the return signal, allowing 'uplink' data transmission. Downlink transmission is achieved by modulating the BS laser source.

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Figure 1(b) outlines how the optical system is arranged. A holographic beamsteering system directs light from to an SD mote via a beamsplitter. The light returned from the SD is focussed onto a camera, forming a bright spot on a pixel or small group of pixels. Operation of the liquid crystal shutter causes intensity modulation of this spot, and this modulation is recovered in software, allowing data transmission from the SD mote to the BS.

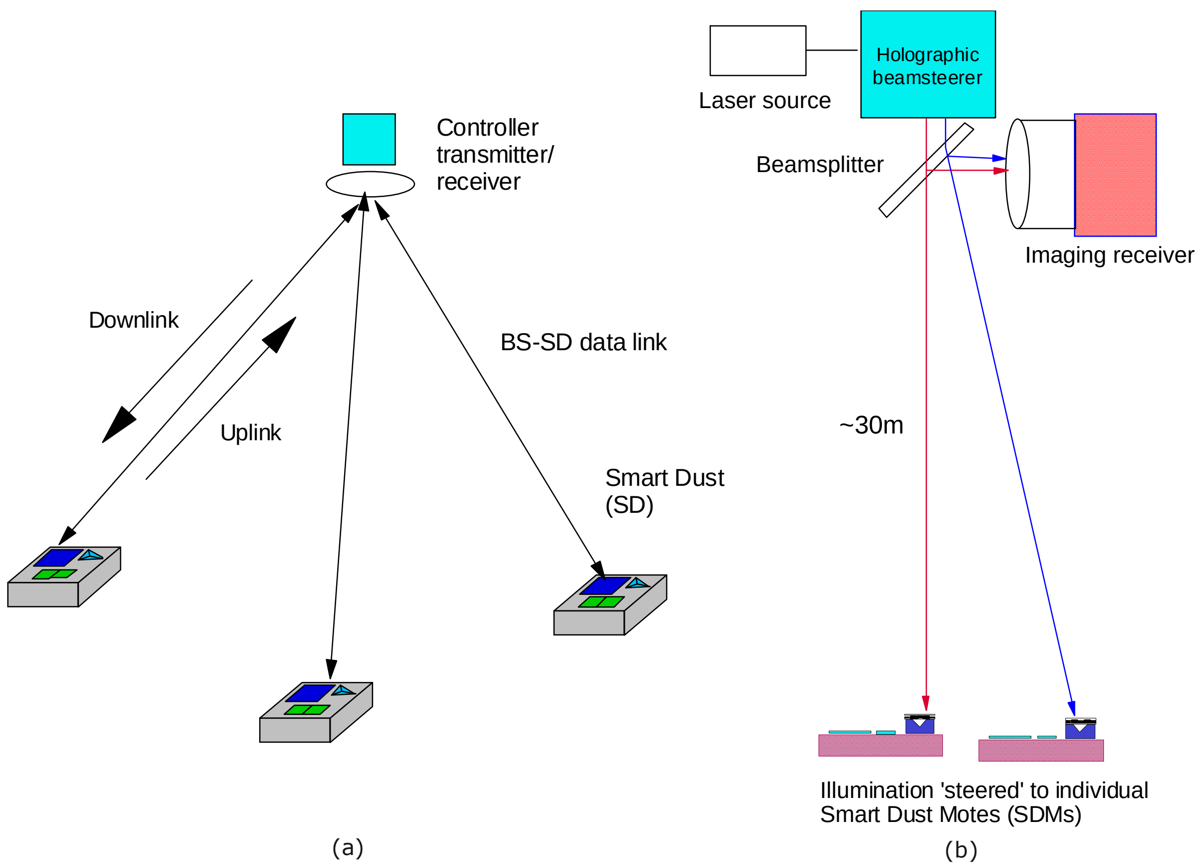
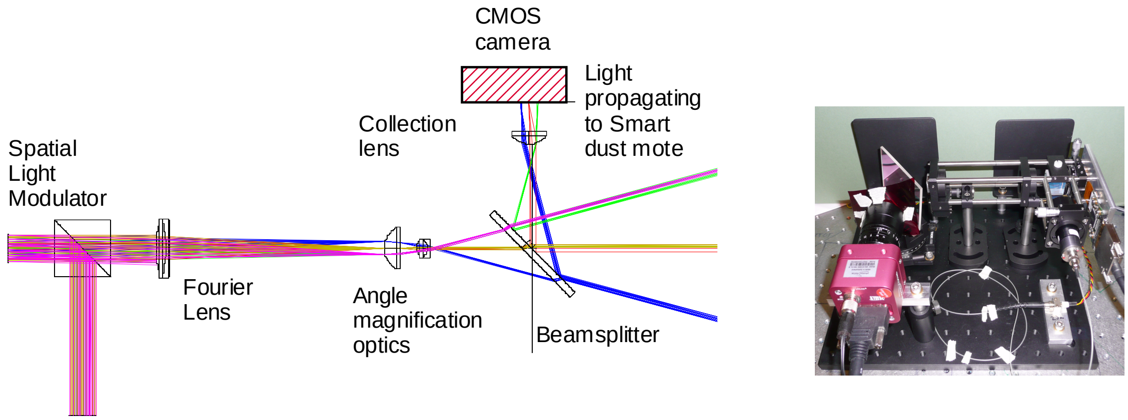


Figure 1. (a) Smart dust concept. (b) System schematic



(a) (b)

Figure 2. (a) Base station schematic. (b) Picture of implementation

2.2 Base Station

Figure 2(a) shows a schematic of the BS. Light from a laser (635nm) is collimated and illuminates a silicon backplane spatial light modulator. This displays a phase grating[11] that diffracts the incoming light through a controllable angle, creating a solid-state beamsteerer. More complex patterns are also used to control focus and aberrations, as well as route to multiple destinations[11]. The steering angle is limited to several degrees by the pixel size (~10µm) so angle magnification optics are used to increase the steering angle to approximately 30 degrees (full-angle). This light then passes through a beamsplitter and propagates to the smart dust. The beam that is returned from the smart dust mote is diverted by the beamsplitter and imaged by a CMOS camera. Figure 2(b) shows a picture of the completed BS.

2.3 Smart dust

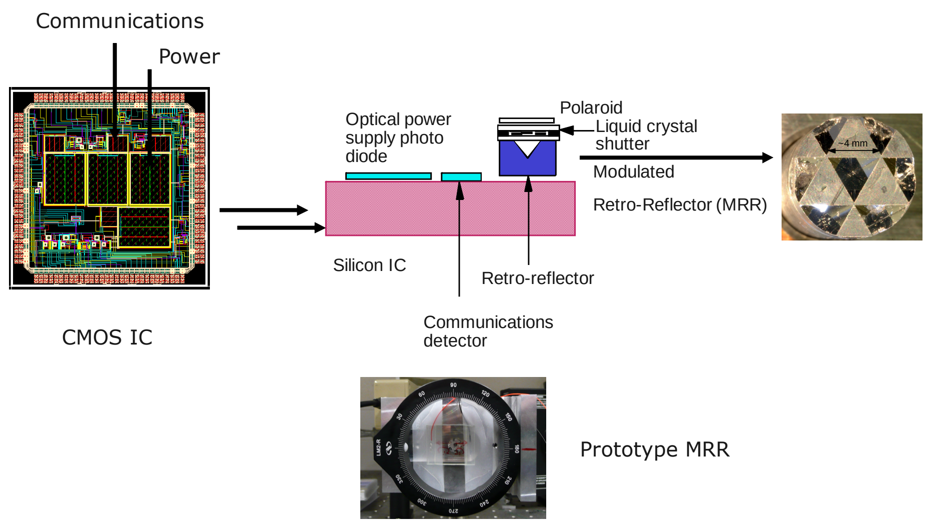


Figure 3. Schematic of smart dust showing individual components

The SD mote consists of a silicon IC fabricated in a 0.18µm twin-well CMOS process, as show in Figure 3[12, 13]. The IC has two power photodiodes connected in series, and these are used to provide between 0.6-0.9V at 10-1000nA depending on illumination intensity (which varies with the distance from the SD mote to the BS). In addition the IC contains a communications receiver, control logic and a liquid crystal (LC) driver circuit. The output from this circuit modulates an LC cell filled with a nematic LC(E7), with anti-parallel alignment, that operates at low voltage[10]. The cell is combined with a small acrylic silvered corner cube and polariser to form a modulating retro-reflector (MMR) as can be seen in the figure. This MRR transmits data from the SD mote to the BS.

2.4 Link budget

For the system to operate there must be sufficient link margin for the downlink and uplink to operate, and for there to be sufficient illumination at the SD mote from the BS laser. Modelling[10] indicates that the limiting factor is illumination. Figure 4 shows a plot of the illumination level at the SD mote vs. range for both ray tracing simulations and calculation (detailed in [10]). Also indicated is the minimum required intensity for correct operation of the system, as determined by measurement (this is approximately 3.5µW/mm^2). It can be seen that a range of approximately 30m should be feasible. This compares with an estimated communications range of >100m.

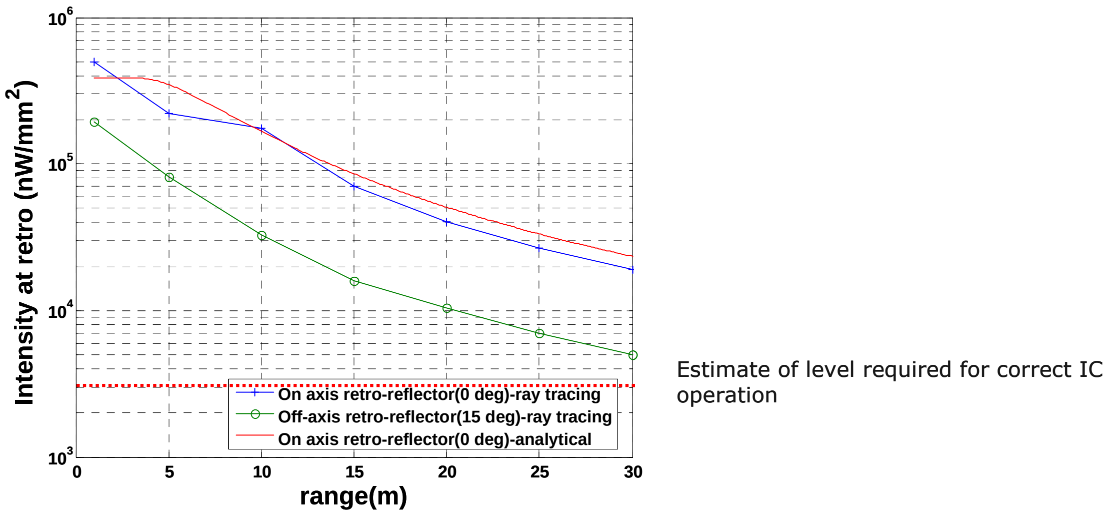


Figure 4. System link budget

3. SYSTEM OPERATION AND EXPERIMENTAL RESULTS

3.1 Base station tracking

The BS must locate the SD motes within its coverage area, and then transmit and receive data. Figure 5 shows a block diagram of this process. The first stage is to find the SD motes, and this is achieved by expanding the beam from the BS using a defocus phase function on the SLM and scanning the coverage area. When the beam strikes the motes there is a 'bright' return from the retro-reflector relative to the background, and the position of this return is determined. This is repeated for all such returns. To communicate with a particular SD mote the beam is focused and a fine tracking algorithm is used to maximise the return from the desired mote so there is sufficient intensity to power and communicate with the mote. As can be seen from the figure the tracking system also incorporates correction for optical system distortions. This is achieved by adding additional pre-calculated focusing 'power' on the routing hologram for off-axis positions to control spot size and by correcting the desired routing angles for barrel distortion using pre-calculated calibration factors.

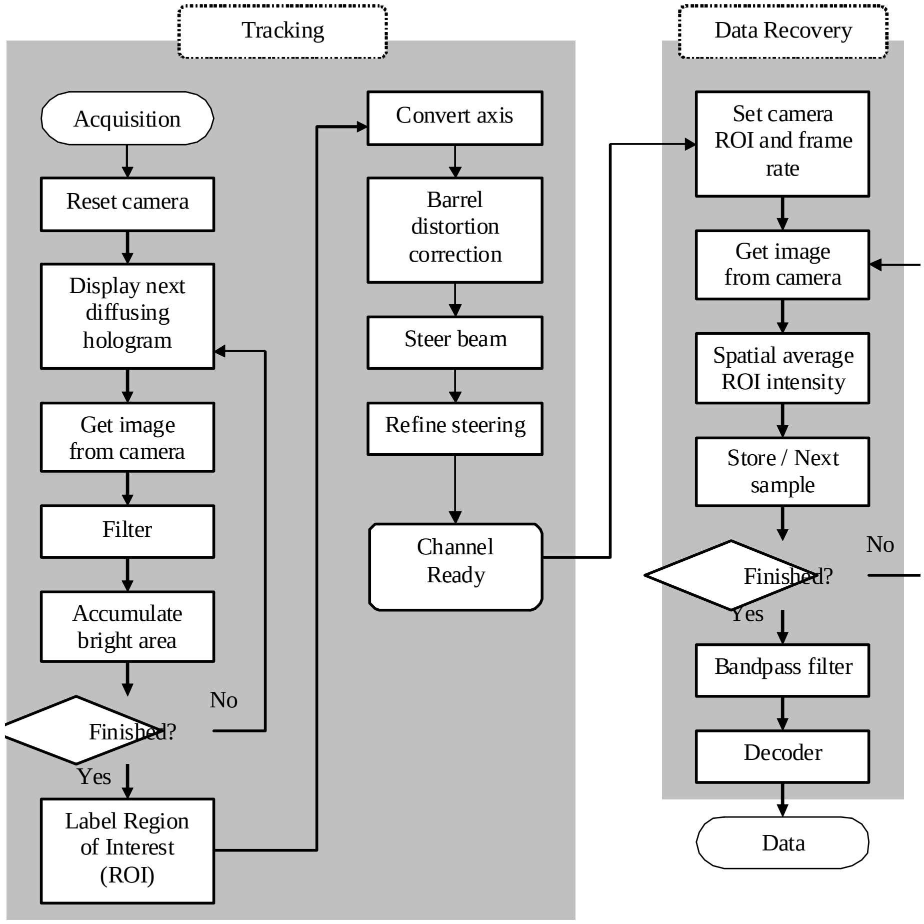


Figure 5. Tracking and acquisition algorithm

3.2 Downlink communications

Figure 6(b) shows a block diagram of the SD mote receiver. In order to operate over a wide dynamic range a logarithmic receiver based on an adaptive element is used[14]. This responds to the contrast ratio of the downlink modulation rather than the absolute value on the photodetector, allowing correct operation for mean photocurrents between 100pA and 100nA. The signal from the receiver is thresholded and inverters are used to buffer the output, which passes to decoding and clock recovery circuitry.

Figure 6(a) shows the downlink waveform. This consists of an 8kHz data clock, with a 1kbit/s Manchester data waveform. The clock is transmitted to the IC as it is extremely difficult to produce a local clock as the power supply voltage of the IC varies with illumination intensity, so providing a 'remote' reference solves this problem. Manchester coding is used so the code is intrinsically balanced, which reduces baseline wander and allows straightforward data recovery.

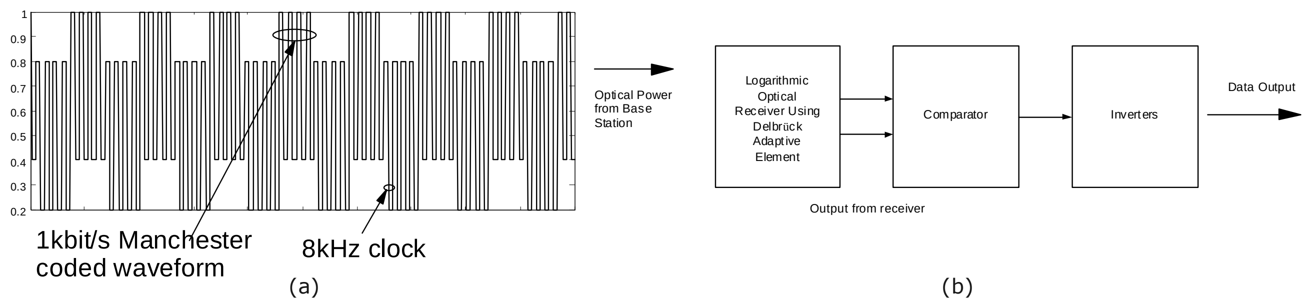


Figure 6. Downlink communications waveform and receiver block diagram

3.3 Uplink communications

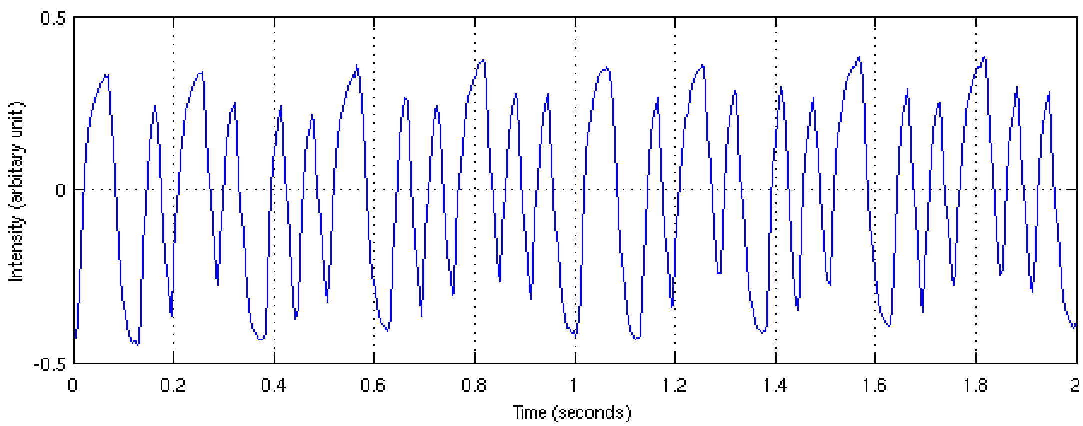


Figure 7. Typical uplink waveform

The uplink is formed between the MRR and the CMOS camera in the base station and uses Manchester coding to transmit data at ~30bits/s. Figure 7 shows a typical received waveform for a link length of 15m, operated in low ambient light conditions. Data recovery is achieved by locating the 'spot' from the desired MRR on the camera, and collecting frames of data from a small Region of Interest (ROI) that includes the spot at a high frame rate in order to oversample the data waveform. The intensity in the ROI can then be integrated, resulting in the waveform shown in the figure. This is then recovered using further filtering and processing [10], yielding an error free data stream.

3.4 End to End communications

The SD mote incorporates simple decoding logic, so that if the downlink sends an ASCII 'U' symbol a signal to switch the LC to the 'up' state is sent from the LC driver circuit, and if a 'D' is sent the LC then switches the other way. This allows a 'loopback' test, with the BS sending a signal to the IC and the uplink returning data to the BS.

At present the MRR is not integrated with the SD mote so it is not possible to illuminate the system with a single beam. A beam is used to illuminate the SD mote and separate beam from the BS is used to illuminate the MRR, which is at a range of approximately 1m. This range is limited by the available BS laser power. The beam to the SD mote forms the downlink and powers the system, and the beam to and from the MRR forms the uplink.

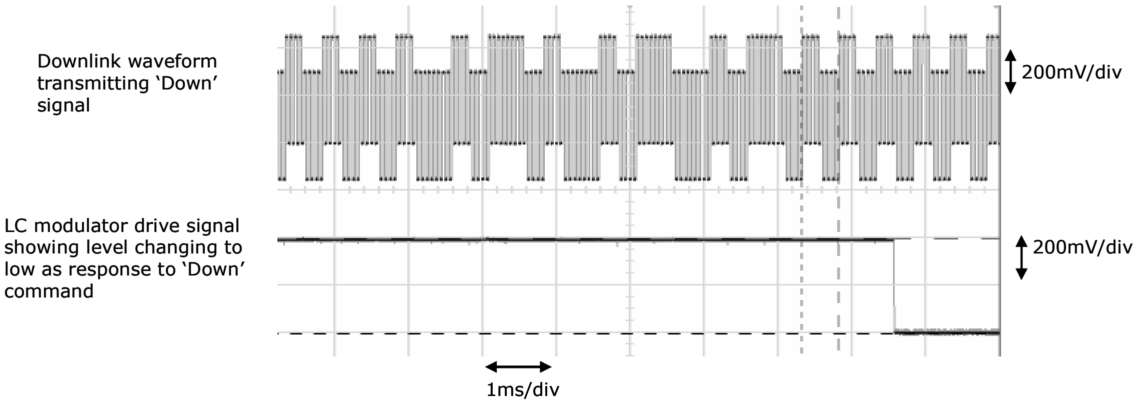


Figure 8. Received waveforms showing decoding of instructions

Figure 8 shows the downlink waveform on the upper trace, containing a 'D' instruction, and the output from the receiver on the lower trace. The decoded instruction can be seen on the lower trace, with the voltage level switching from high to low. Figure 9 shows the receiver output on the top trace, responding to a series of 'U' and 'D' instructions sent on the downlink. This output is fed to the LC modulator drive circuit which generates the electrode voltages shown. The difference between these voltages is displayed on the lower trace, and this is the net voltage applied across the LC cell. The pulses are arranged to change the state of the LC, then apply no voltage, and apply the reverse voltage to change it back again. More detail on this aspect of the system can be found in [10].

The electrode drive voltages are connected to the LC cell, and the modulated uplink signal is recovered by the CMOS camera and software based receiver in the BS. Figure 10 shows the waveform after recovery, showing that the on-off waveform is received correctly. This shows that the system successfully performs the 'loopback' test, albeit over short ranges.

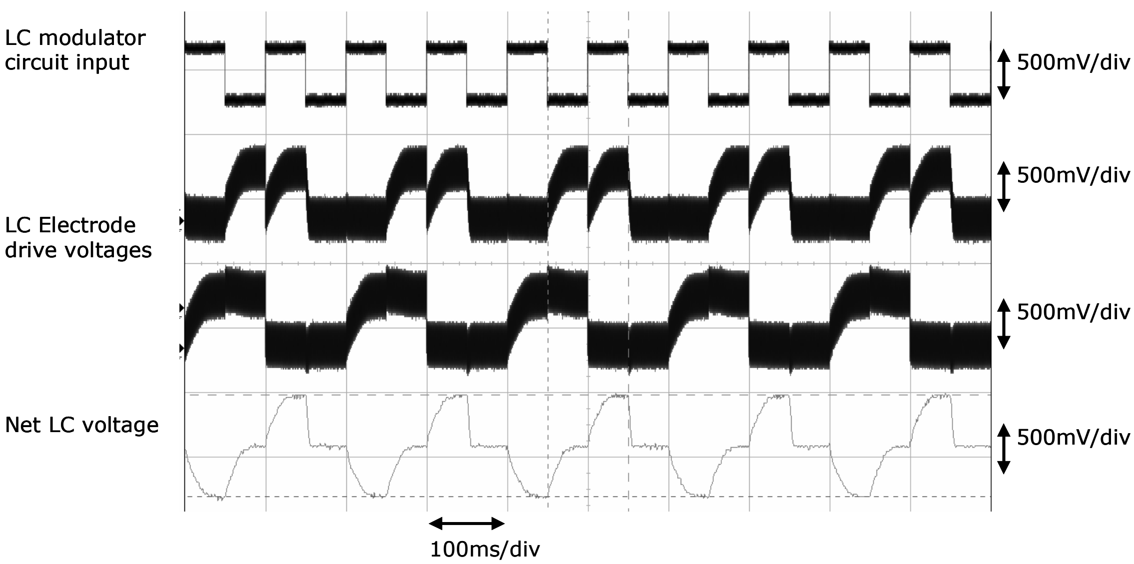


Figure 9. Waveforms decoded by SD mote

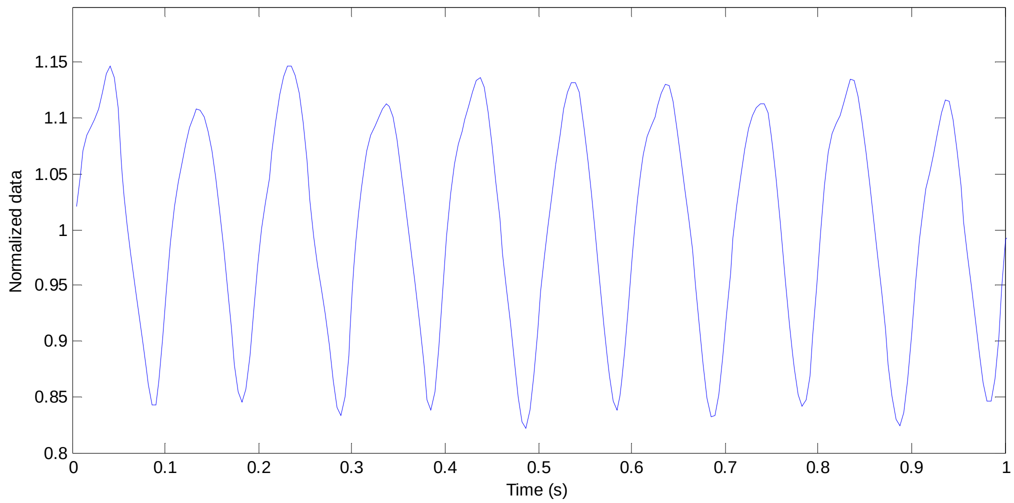


Figure 10. Waveforms received by BS from uplink

4. DISCUSSION AND CONCLUSIONS

The results presented here show that a self-powered mote can successfully communicate using an MRR based link, and that such motes can have very low energy consumption. In this case the modulator requires an energy (assuming CV^2 with C=28pF for a modulator area of $1mm^2$ and V=0.5V) of $7pJ/bit/mm^2$ so the communications energy used at the node can be extremely small. The challenges for this type of system are to increase the communications range and to deal with situations where there is no line-of-sight. Work to increase the range, using higher power illumination, is underway, as are plans for integrating the MRR components.

Architectures that use RF and optical links can overcome the problem of blocked RF links. In this case optical links are used when there is a line of sight to the BS, with RF links to 'cluster heads' that have sufficient connection to the BS [15]. Modelling has shown significant energy saving compared with all RF architectures even if there are only a small proportion of nodes with line of sight to the BS. There are architectural advantages also, as routing between nodes is simpler than a fully ad-hoc configuration. There are also similar hybrid network examples that operate over much greater ranges[16].

Using large numbers of small sensor nodes whilst reducing the energy consumption associated with human occupation are conflicting goals, and achieving very low power systems that can scavenge existing resources is likely to be a part of the means to achieve this. The work presented here shows that communications at very low energy levels is feasible, but there are still many challenges in implementing the high levels of functionality that will be expected in deployed systems.

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