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Optical wireless communications and potential applications in space

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Abstract— **Indoor optical wireless has made good progress recently, with rates of 100s of Mbit/s demonstrated using visible light communications and Gbit/s optical wireless systems operating in the infrared region of the spectrum. Space is a potentially attractive environment for optical wireless, due to the line of sight channels that are available between objects in space, and the requirements for low mass systems of the type that optical wireless can potentially produce. In this presentation we review some of the recent progress in indoor applications, including details of systems implemented at the University of Oxford, with an emphasis on how they might be used in a space environment.**

Keywords-optical communications; optical wireless

I. INTRODUCTION

The growing congestion in the RF spectrum, and the increasing demands for higher data rates, has led to optical wireless being an active area of research. Recently, there has been progress in several areas. Solid-state lighting is becoming a viable competitor to other light sources, and the LEDs used in such applications can be used for communications as well as illumination. Visible Light Communications (VLC) originated in Japan (see work from the Visible Light Communications Consortium (VLCC) for instance[1]) and is now an active field of research worldwide, including a published IEEE standard (see [2]). In the field of more 'traditional' infra-red optical wireless there have been demonstrations of extremely high data rate point to point links[3], as well as systems operating at Gbit/s[4]. The energy used in optical wireless can be used to power small systems, and combining communications and power supply is attractive in certain circumstances, with recent examples of implementations[5].

There is a long history of optical wireless research applied to space applications (see for example[6]). This paper presents recent developments in indoor optical wireless, together with brief comments about their potential application in space. (It should be noted that the examples given are by no means the only ones in these well-researched areas.)

II. VISIBLE LIGHT COMMUNICATIONS

For spaces which are occupied and need illumination solid-state lighting based on Light Emitting Diodes (LEDs) can offer highly reliable and efficient lighting, at DC operating voltages compatible with those produced by photovoltaic panels. This makes them potentially attractive to illuminate manned vehicles, and this infrastructure can also provide broadcast (unidirectional) communications in a straightforward manner.

In a typical system a DC bias is applied to an LED to provide the illumination with additional modulation for information transmission. Most LEDs used to provide white light are a blue LED combined with a phosphor layer that emits yellow light. White light is formed by the combination of the blue component that is not absorbed by the phosphor, and the emission from it. The 3dB bandwidth of the white LED is several MHz, which increases to approximately 10MHz for a typical device if the slow phosphor response has been filtered out using a blocking optical filter on the receiver.

In a well-lit environment, the signal to noise ratio available at a typical optical receiver (a collection area of ~1cm^2 and a field of view of 120 degrees with a bandwidth of ~20MHz) might be greater than 50dB, so the VLC channel is 'low-bandwidth, high signal to noise ratio'. High-order modulation schemes such as Orthogonal Frequency Division Multiplexing (OFDM)[7], equalization[8], and parallel transmission[9] can all be used to increase data rate, with rates of greater than 500Mbit/s demonstrated for a single LED[10] using OFDM for example.

Most space applications do not require human intervention and illuminated areas however, so it is thought that VLC has limited application in these areas, although the developments in complex modulation schemes applied to high power, low bandwidth LEDs may be applicable to other wavelength emitters where there are applications in a space environment.

III. INFRARED OPTICAL WIRELESS

Optical Wireless (OW) communications can be achieved using Line-Of-Sight (LOS) channels, or non-LOS (NLOS) configurations. In diffuse systems a wide field of view transmitter illuminates the space to be covered and reflections and scattering from surfaces creates multiple paths from transmitter to receiver. These paths create a channel that is robust to blocking, but has high path loss and dispersion making it challenging to achieve high data rates. For this reason work at Oxford has focused on high speed LOS systems.

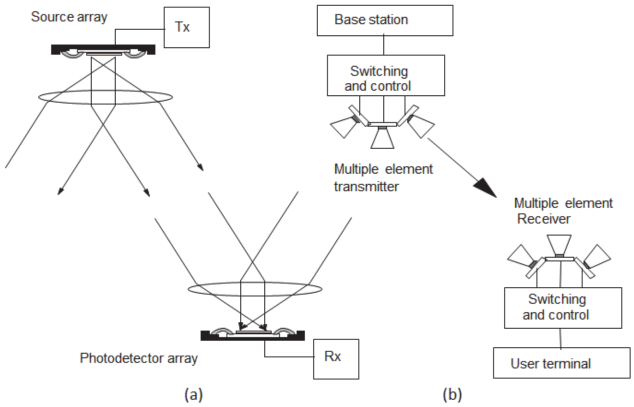
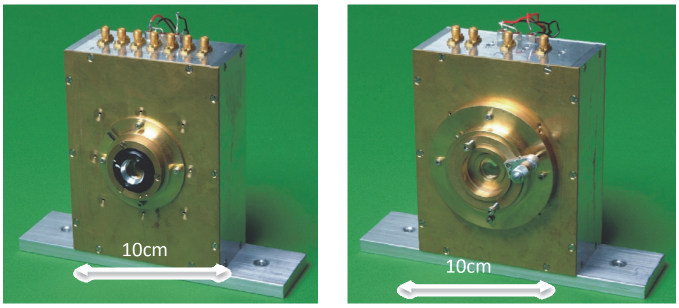


Figure 1. Approaches to high-speed optical wireless. Imaging(a) and Angle(b) diversity.

In LOS systems the transmitter can 'see' the receiver, which collects a proportion of the emitted light, depending on the field of view of the system. LOS systems can have low path loss, and the channel has no dispersion. The bandwidth in this case is limited by available transmitter and receiver components. A simple analysis of the link budgets available for a single channel link shows that creating a system with high data rates and coverage requires multiple transmitter and receiver channels[11]. Figure 1 shows the two standard approaches to this. In imaging diversity[12] an array of sources is combined with an optical element and this creates a cellular illumination pattern. The receiver contains an optical element that maps light from a particular angle to a single element of a detector array. This allows compact components, but requires custom devices. Angle diversity[13] uses multiple single element transmitters and receivers, together with control and switching to obtain coverage. The advantage of this approach is that commercial devices can be used, with the disadvantage that a bulky system often results.

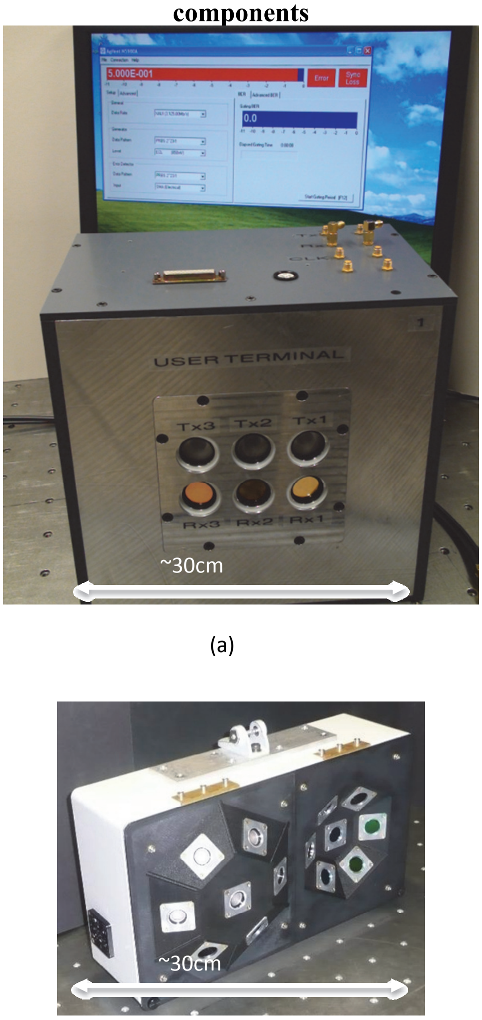
An integrated imaging diversity transmitter and receiver was developed by Oxford and partners from Huddersfield, Imperial and Cambridge Universities, and transmitter and receiver components from this are shown in Figure 2. This had seven channels, with a full angle field of view of ~12 degrees and operated at ~200Mbit/s (details can be found in [14]). It can be seen that the use of custom devices and components can lead to a compact transceiver.

Figure 3 shows terminals from two angle diversity systems that were developed as part of a European Commission (EC) funded project (OMEGA). Figure 3(a) shows a terminal from a bi-directional Gbit Ethernet system. This uses three transmitters and three receivers on each terminal, with an overall field of view of ~25x8 degrees and a range of 3-4m operating at a Bit Error Rate of 10^{-9}. At such rates the field of view and range is constrained by the area of the photodetectors available (0.5mm diameter avalanche photodetectors in this case). In order to build a room-scale demonstration a system with a reduced rate of 280Mbit/s was developed, with three terminals identical to that shown in Figure 3(b). The data rate, and hence bandwidth, reduction allowed a ~2mm diameter avalanche detector to be used, increasing collection area by a factor of approximately 15. This offers increased range and field of view for the single links. In this case the field of view (full angle) of each terminal was approximately 90 degrees, with a range of up to 10m on boresight alignment (at a Bit Error Rate of 10^{-9}). Details of these systems can be found in [15] and [16] respectively, with videos available on the OMEGA website (www.ict-omega.eu)



(a) (b)

Figure 2. Imaging diversity transmitter (a) and receiver (b) components



(a)

(b)

Figure 3. Angle diversity terminals (a) Gbit Ethernet, (b) 300Mbit/s device

The major constraint in the design of such systems is the field of view at the receiver (which is limited by the detection area). This affects the amount of tracking the receiver requires to be able to 'see' the transmitter. For indoor applications terminal mobility is a key requirement, so this field of view of the receiver should be matched to that of the transmitter. However in space applications where terminals might be fixed, for instance for intra- platform communications full coverage might not be a requirement, and modified components with better range and/or rate are feasible.

IV. SMART DUST

The OW systems mentioned in the previous section are symmetrical, with identical terminals and bidirectional communications with similar data rates in both directions. For many systems, such as sensor networks, an approach that uses a complex 'Base Station' (BS) and simple terminals is highly attractive.

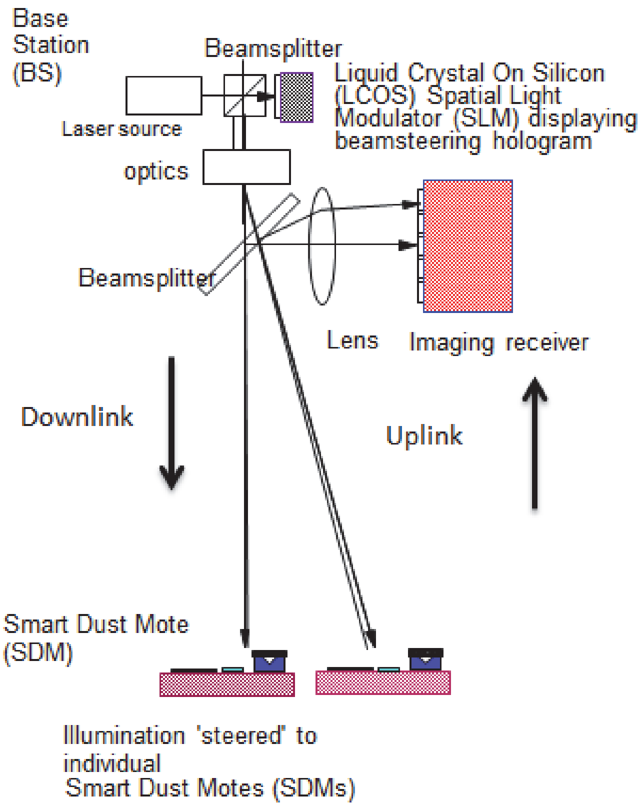


Figure 4. Smart dust architecture

The University of Oxford have developed such an architecture, where a complex BS communicates with a simple sensor node (or 'Smart-dust' [17]). Figure 4 shows the architecture, and full details of the system can be found in [5]).

The system uses a beamsteering technique to illuminate the nodes with a narrow beam of light. The BS uses an extremely flexible holographic beamsteerer, effectively a programmable hologram, which can steer multiple beams of light to different sensors independently, efficiently locate and track them, and correct for any aberrations in the optical path. Figure 5 shows the current BS implementation.

Light from the BS propagates to the smart dust mote, and a retro-reflector returns the beam to the base station, where it is detected using an imaging receiver that is implemented using a CMOS camera. The returned beam can be modulated using a liquid crystal shutter that is placed over the retro-reflector at the smart dust mote. A downlink (from BS to smart dust mote) is formed by modulating the laser source used in the BS, and an uplink (from smart dust mote to BS) is formed by modulating the liquid crystal shutter.

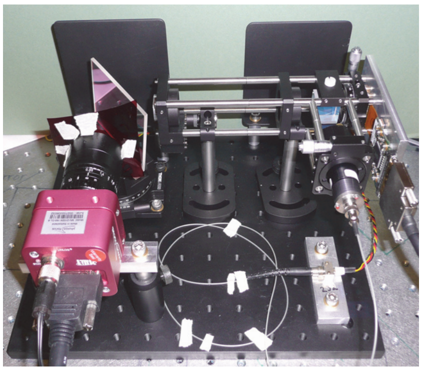


Figure 5. Base station implementation

Figure 6 shows a schematic of the smart dust mote. This consists of a custom CMOS integrated circuit that contains a communications receiver to detect the modulated downlink, a controller for the liquid crystal shutter (to send data to the BS), and power supply photodiodes. Illumination from the BS and light scavenged from the environment provides power to the system. At present the system operates in an indoor environment, and the data rates are kbit/s for the downlink and 10s of bits/s for the uplink (limited by the liquid crystal modulator).

This architecture has some promising aspects for communications within and between spacecraft. Concepts that use a central control craft with smaller sensors in a constellation that orbits together are well-suited to the complex BS simple terminal concept. The optical channels can be highly flexible and reconfigurable and the retro-reflecting communications allows very simple sensor nodes that do not require tracking elements. At present the major components are based on liquid crystals, so there may be issues in adapting their use. At the BS the LC modulators have limited temperature range, and at the smart dust mote their data rate is limited. Multi-quantum well modulators can be used for retro-reflecting links[18] with high rate (10-100Mbit/s) demonstrations of over km[19] terrestrial links being reported, so these may provide suitable devices for use in space.

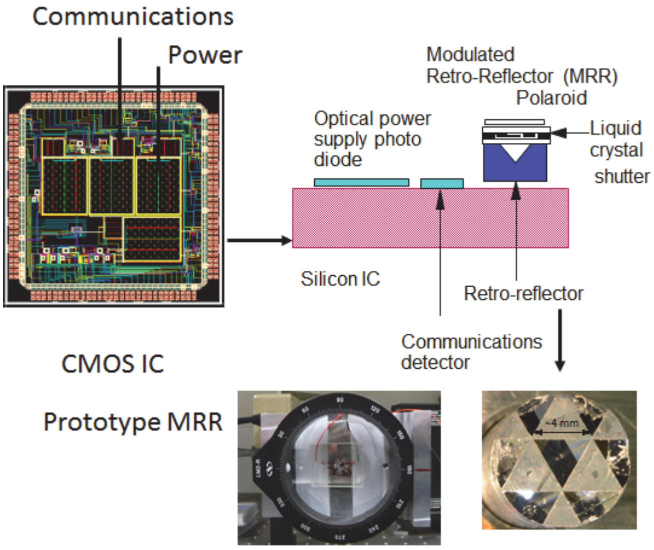


Figure 6. Smart dust mote IC layout

V. CONCLUSIONS

This paper has presented a brief overview of developments in indoor optical wireless communications, as well as novel sensor networks that use optical wireless communications.

There is no doubt that some of the components and systems approaches might be applied to space communications, although identifying the specific implementations and constraints will require dialog between the indoor optical wireless community and those involve in space research. It is hoped that this brief overview might stimulate such work.

ACKNOWLEDGMENT

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