Free-Space Optics Based Wireless Sensor Network Design

P. Verma, A. K. Ghosh and A. Venugopalan

Telecommunication Engineering Program
School of Electrical and Computer Engineering
University of Oklahoma Tulsa
Tulsa, OK 74135.
pverma@ou.edu

Abstract

This paper proposes an FSO-based mobile sensor network that is not subject to RF interference common to wireless sensor networks. FSO-based mobile sensor networks can potentially be used in a battlefield where security of communication, including freedom from susceptibility to enemy-induced jamming, is important. The paper discusses the design of nodes containing multiple transceivers composed of LEDs and photo detectors. Results of initial experiments are included. The work reported in this paper is part of an ongoing investigation on mobile FSO networks, including the design of efficient protocols that can allow the mobile sensor nodes to function as a mesh network permitting information exchange among nodes directly and, possibly, through an intermediate node.

Introduction:

A wireless sensor network (WSN) that comprises of small-scale, low-cost processors with integrated sensing, communication and data processing capabilities is popular in many domains such as battlefield surveillance, habitat monitoring, home automation and health-care applications [1,2]. All the WSNs use radio frequency (RF) for communications. Thus, in an environment where there is an unacceptable level of RF interference, or where the leakage of RF has the potential to compromise security, it is undesirable to deploy RF based WSNs. In environments with electronic instruments that are susceptible to RF interference, the presence of RF from a WSN might lead to malfunctioning of such instruments resulting in potentially catastrophic consequences. Several papers have discussed various approaches to building WSNs using optical wireless or free-space optical communications [3-10].

In this paper, we discuss our research on developing a low-cost free space optics (FSO) based WSN in situations where an RF based WSN is not desirable. We have developed a low-cost free-space optical ID system for high-security identification and interrogation [11] in our laboratory. Our focus in this paper is on extending the optical ID system using angle-diversity photodetectors [12-14] so that sensor-to-sensor wireless communication is possible over a distance of several meters. The angle diversity photodetectors also allow for a limited amount of mobility between the sensor nodes on a planar surface.

Optical ID System:

The optical ID system is developed for securely interrogating an optical tag using a laser beam based optical wireless communication system. The Optical ID system comprises of two components, an optical reader and a tag. Figures 1 and 2 present block diagrams of how the tag and reader systems are made. Only sending an encrypted message from the optical reader can activate this tag. When we want to acquire data from the tag, we turn on the optical reader. The optical reader sends a coded light pulse to the tag. The tag, on receiving the light pulse, verifies that it is from the reader and then activates the transmitter of the tag. The tag can be interfaced to a sensor. The information stored in the sensor node is processed and digitized for transmission. When interrogated by the reader the information from the sensor is provided to a transmitter circuit. The transmitter modulates and transmits the information at a suitable frequency. The optical reader locks in to this modulating frequency and acquires the sensor information.

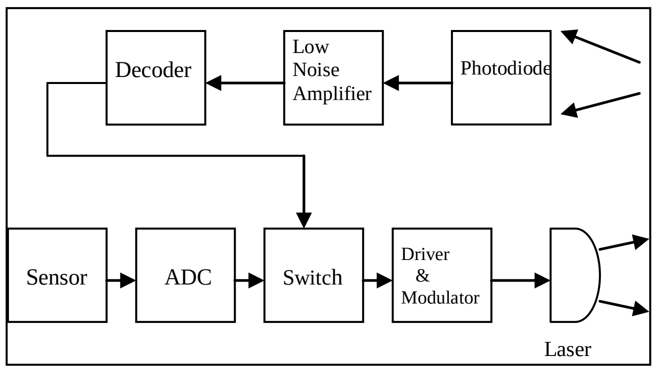

Fig 1: A block diagram of an optical tag with a sensor

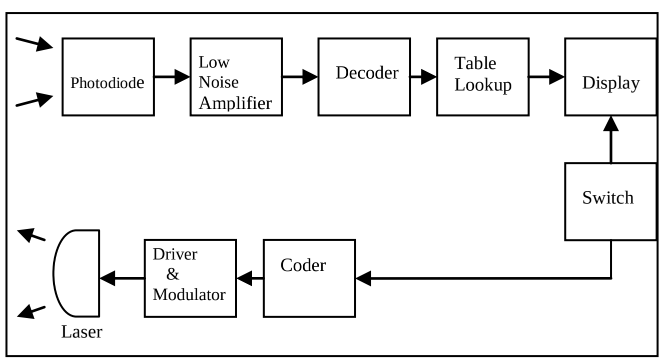

Fig 2: A Block diagram of the optical reader.

Our optical ID system has been built with off-the-shelf components at a moderate cost to provide a high degree of security. One aspect of security is provided by means of a directional laser beam and the other part through an RSA encryption scheme. We use low-cost low-power diode lasers with a wavelength of 635 nm. The receivers are made with 1 cm diameter Silicon p-i-n photodiodes. The system operates at a data rate of about 20 Kbps. The bit rate chosen keeps the cost down and is adequate for our reader-tag system that needs to send only a few hundred kilobytes of information. We carried out several experiments to determine our system's performance under various conditions.

To determine the performance of the system at various distances and states of alignment, we characterized the beam emitted by the laser. We find that the minimum spot sizes are $W_{0x} = 66.2$ µm and $W_{0y} = 242$ µm along the x and y axes respectively. The beam divergence angle is calculated to be 4.28 mrad. This highly paraxial beam provides our system with a large amount of security. The optical power received by the tag from the reader with a variation in distance is also studied. The value of normalized received power decreases to less than or equal to 0.5 when when the tag and reader are separated by 5.15 m. Thus we find that our optical-ID works well if the distance between the reader and the tag is kept below 5.15 m. We find that at a distance of 3 m a lateral offset of ±3.5 mm from the axis can be tolerated without sacrificing 80% of the received power. From BER measurement we find that a decrease of 20% power at the distance of $z = 3$ m does not degrade the BER. The frequency response of the laser plus photo detector combination has been determined. The 3 dB cutoff frequency measured lies between 50 KHz to 220 KHz depending on the manner of modulating the laser driver.

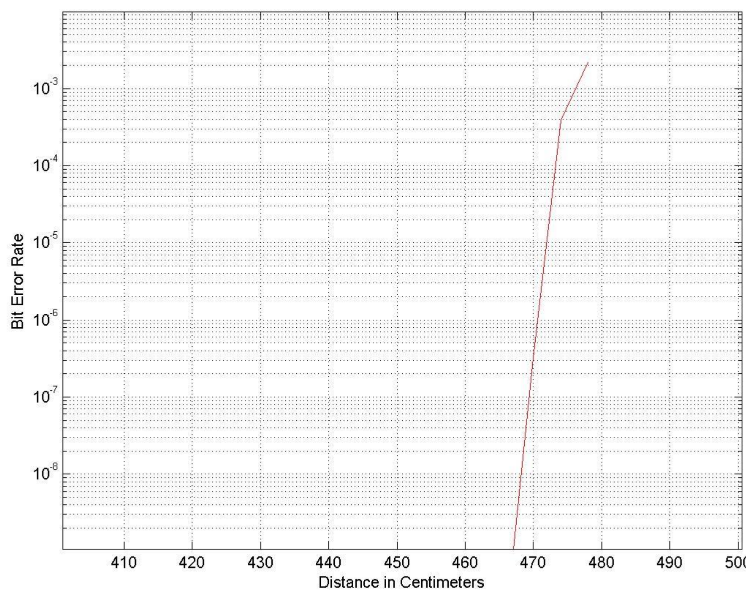

Fig 3: Bit Error Rate versus Distance for transmission at 19.2 Kbps

To understand the performance of our intensity modulated direct-detection optical-ID system we measured the bit-error-rate in a typical set-up. Tests were conducted using varying bit rates and data sequences. Bit error rate is a strong function of signal power. As we move the tag further away from the reader, the power received by the tag decreases along with the signal to noise ratio. Beyond a certain distance, we can no longer recover the signal. In our experimental investigation, we have measured the limit on the distance beyond which the system exhibits significant loss of packets. The variation of the bit-error rate with distance is plotted in Fig. 3. We find that we can use the optical ID with an error rate less than 10^{-9} when the distance between the tag and the reader is up to 4.6 m.

FSO System based WSN:

Based on the design of the short distance, point-to-point free space optical ID system in our laboratory, we envision a WSN where each sensor node is equipped with an optical transmitter and an optical receiver made with an array of p-i-n photodiodes arranged as shown in Fig. 4. We assume that the sensor-nodes are distributed on a planar surface, as for example, the floor of a workshop or a level field. Each transmitter emits a horizontal beam of light encoded with its message for other nodes. If illuminated by this beam, the photodiodes of another node can receive the message in the manner of a free-space optical communication system [15]. Thus, our system is based on line-of-sight optical communications rather than the diffused or scattered light based indoor optical communication systems discussed in Refs. [12-14, 16]. Major advantages of line-of-sight communications are large distances between nodes and freedom from multipath interference or fading.

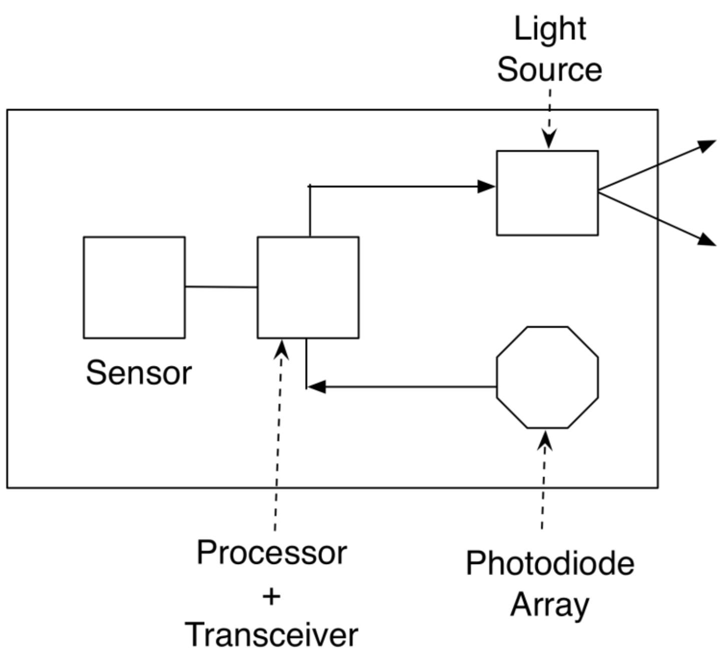

Fig. 4: Block diagram of a sensor node equipped with an optical transceivers.

Unlike the optical ID system discussed earlier, the proposed WSN system uses superluminescent light emitting diodes (SLED) in its transmitter. These SLEDs are capable of emitting light of high intensity (100-2500 mW) over a cone of fairly large angle. They are reasonably fast having rise times of the order of 80 ns [17]. We use an intensity modulated subcarrier scheme in which each transmitter is assigned its unique subcarrier frequency in the MHz range. However it is also possible to use code-division multiplexing.

For the receiving antenna, we have designed an angle-diversity combination of photodiodes connected to each node of the WSN [12]. The photodiodes are arranged in one plane capable of direct detection of light from a SLED located in the plane. All the p-i-n photodiodes in the cluster are connected in parallel so that the photocurrents are added together in the preamplifier stage. The photodiodes receive lights from SLED transmitters of the WSN. Only when the proper subcarrier signal is received by one of the photodiodes the communication link is established. A schematic diagram of the angle-diversity photodiode cluster is shown in Fig. 5. Each photodiode is equally weighted and the sum of the signal currents of the photodiodes is demodulated and decoded to retrieve the data.

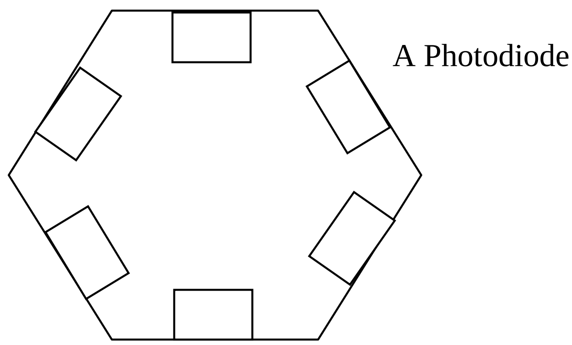

Fig. 5: A cluster of six photodiodes capable of receiving light from various directions. The photodiodes are connected in parallel.

A schematic diagram of our FSO based WSN with nodes distributed on a planar surface is shown in Fig. 6. More than one node can receive the signal from a particular SLED transmitter because of the large cone of emission for each transmitter. So if we arrange the photodiode cluster based receivers carefully we can easily realize a FSO mesh network. As long as the photodiode cluster of a particular node remains in the field of view of the SLED transmitter of another node, a communication link between the two can be potentially established. Thus a degree of mobility between two nodes is permitted in the proposed FSO based WSNs.

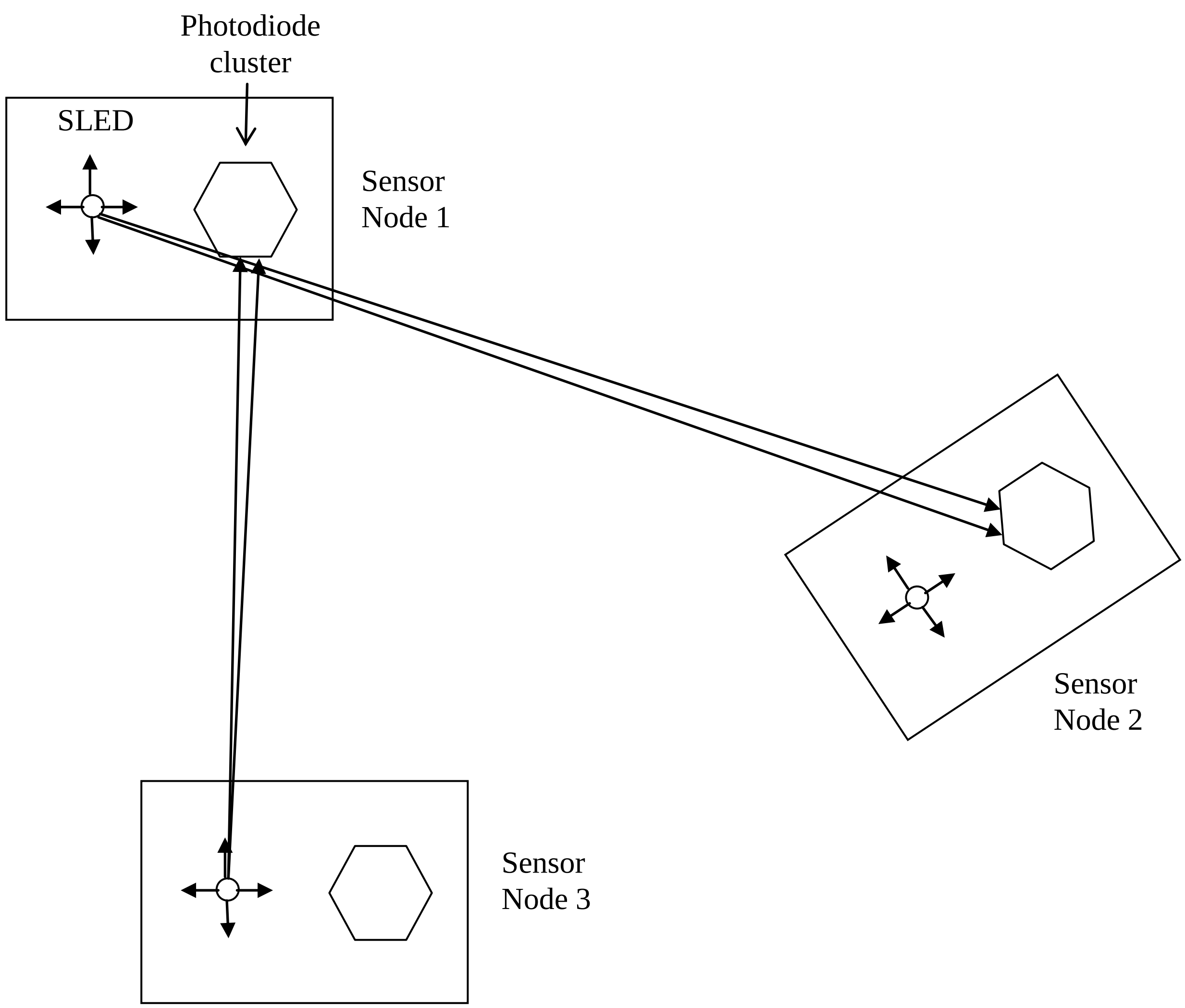

Fig. 6: A FSO based WSN with three sensor nodes with node 1 talking to node 2 and node 3 talking to node 1.

Design:

At first we built a FSO system with a laser based transmitter and a cluster of identical p-i-n photodiodes as shown in Figs. 4 and 5. We combined several reverse-biased photodiodes in parallel with a simple op amp based transimpedance preamplifier. The bandwidth of the preamplifier was kept much lower than that of the photodiodes. As a result, the bandwidth of the multiple photodiodes and the transimpedance stage weakly dependent on the number of photodiodes used as shown in the frequency response in Fig. 7. In Fig. 7 we depict the frequency response of a receiver with a single p-i-n diode along with those from receivers with 3 or 5 identical p-i-n diodes connected in parallel. The bandwidth of the optical receiver with a single diode is 65 KHz whereas the bandwidth of a receiver with 3 photodiodes in parallel is 58 KHz. When the number of photodiodes is increased to five the overall bandwidth decreases to 47 KHz. The main reason for the decrease is the increase of the capacitance of the reverse biased photodiodes connected in parallel. This decrease is modeled in the calculation of the signal to noise ratio of our optical receivers.

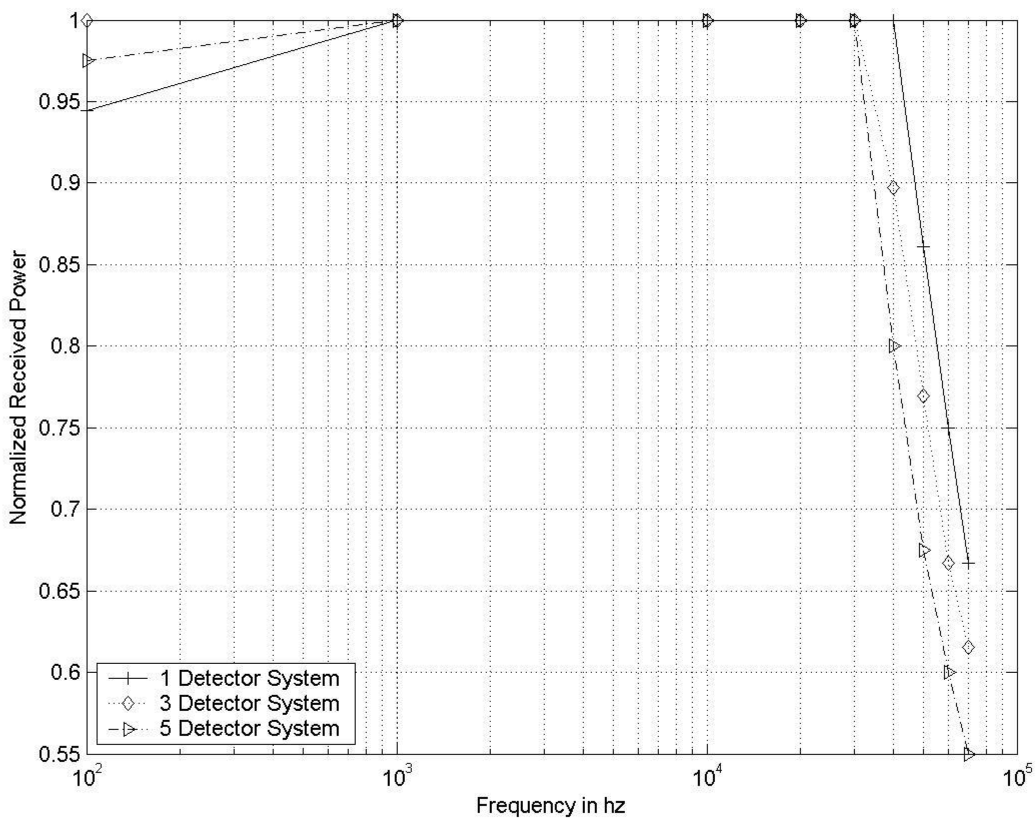

Fig. 7: Frequency response of an optical receiver with multiple photodiodes connected in parallel.

To quantify the potential advantage receiver design with identical photodiodes connected in parallel, we calculate the signal to noise ratio. We assume that the light beam coming to a photodiode cluster is a uniform plane wave whose direction of propagation lies in the plane containing the axes of the photodiodes. We assume that the intensity I_{in} of the input beam is modulated sinusoidally by a signal of frequency ω_s so that

$$I_{in}(t) = I_0\left[1 + m^2/2 + 2m\exp(j\omega_s t)\right] \quad (1)$$

where m is the modulation index and I_0 is a constant. If the area of a photodiode is a and the half angle of the field of view of a photodiode is φ the optical power received by the photodiode is

$$I_{in} a\cos(\theta)\mathrm{rect}(\theta,\phi) \quad (2)$$

where θ is the angle between the axis of the photodiode and the propagation vector of the incoming wave and rect(θ,φ) = 1 for $-\varphi < \theta < \varphi$ and zero otherwise. Considering Eq. (2) and the fact that there are N photodetectors with an angle $\alpha = 2\pi/N$ between them we can write that the total signal current generated by the photodiode cluster is given by

$$i_{sig}(t) = 2mRI_o a f_N(\theta)\exp(j\omega_s t) \quad (3)$$

where R is the average responsivity of the photodiodes and angle-diversity factor

$$f_N(\theta) = \text{rect}(\theta, \pi/2)\sum_{i=1}^{N}\cos(\theta - i\alpha)\text{rect}(\theta - i\alpha, \phi). \quad (4)$$

Thus the signal to noise ratio at the output of the receiver is given by

$$\text{SNR} = \frac{2(mRI_0 a f_N(\theta))^2}{\langle i_{sh,N}^2\rangle + \langle i_{th,N}^2\rangle} \quad (5)$$

where $\langle i_{sh,N}^2\rangle$ and $\langle i_{th,N}^2\rangle$ represent the mean square values of the shot noise and thermal noise currents, respectively. The mean square value of the shot noise current is given by

$$\langle i_{sh,N}^2\rangle = 2qRI_0 a(1 + m^2/2) f_N(\theta) B_N + 2qRI_{Back} aNB_N + 2qi_{dark} NB_N \quad (6)$$

where B_N is the noise equivalent bandwidth of the photodiode cluster combined with the amplifier, I_{back} is the average background light intensity, i_{dark} is the average dark current in the photodiodes and q is the electronic charge. The mean square value of the thermal noise current is given by

$$\langle i_{th,N}^2\rangle = 4kTB_N F/R_L \quad (7)$$

where k is Boltzmann constant, T is the device temperature in ^{o}K, R_L is the load resistance and F is the amplifier noise factor.

If the field of view of each photodiode is large then the angle diversity factor in Eq. (4) can be greater than unity and increase rapidly with N. When $\varphi = \pi/2$ the angle of view of each photodiode is the maximum and each detector can receive a beam of light easily for $-\pi/2 < \theta < \pi/2$. The same beam of light can then be detected by several photodiodes and the value of the total signal current in the receiver increases. In Fig. 8 we show the behavior of $f_N(0)$ as a function of N when $\varphi = \pi/2$. However, if the field of view of the photodiodes is narrow then each photodiode acts individually and $f_N = 1$.

From Eq. (5) we find that when the field of view is wide the signal power at the output of the receiver increases by a factor of f_N^2 whereas the power of the shot and thermal noise grows by factors of f_N and N. In this situation the signal to noise ratio of the photodiode array can increase with N. But if the field of view of each photodiode is narrow then an increase of photodiodes increases the amount of shot noise and the signal to noise ratio decreases with N. In Fig. 9 we show the upper and lower bounds on the signal to ratio for a particular case study. When the photodiodes have a field of view $\varphi < \pi/2$ the signal to noise ratio will remain in between the two bounds shown in Fig. 9.

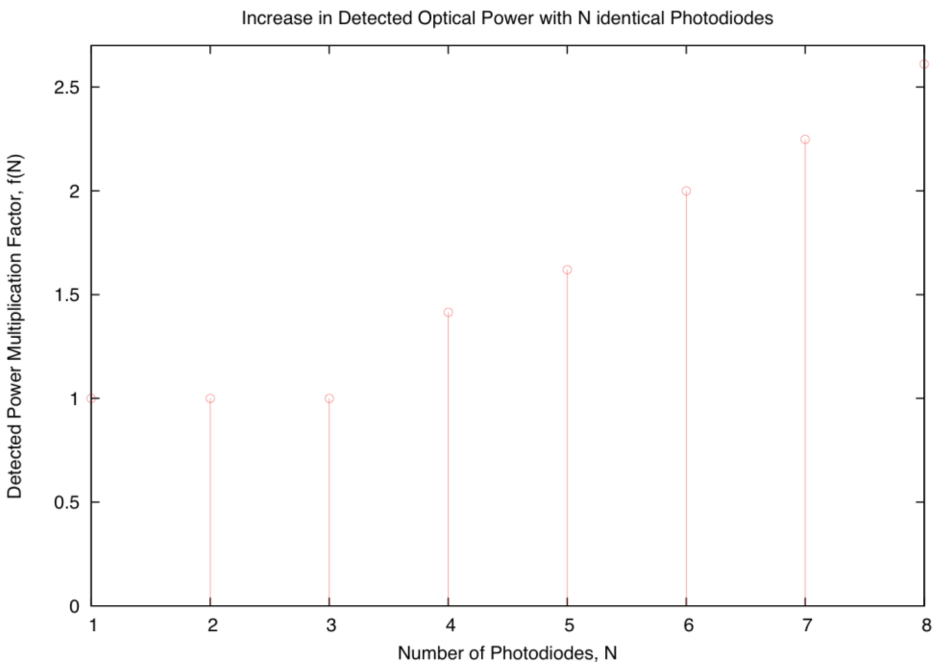

Fig. 8: Growth of the angle diversity factor f_N with N when $\varphi = \pi/2$.

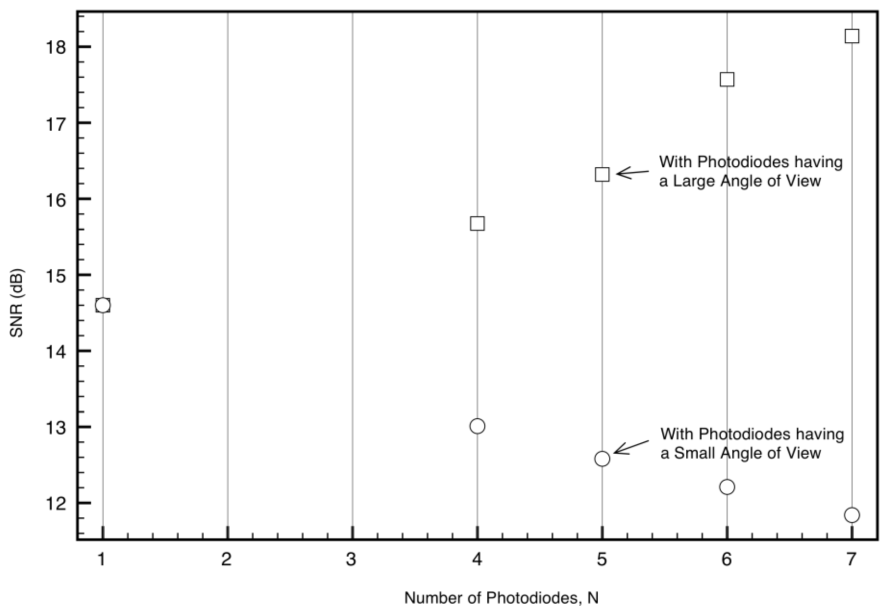

Fig. 9: Upper and lower bounds on the SNR of the photodiode cluster with the number of photodiodes.

Conclusions:

This paper has discussed the design and initial experimental results of a wireless sensor node network using free space optical communication. The network contains nodes that may have a limited amount of mobility, depending on the number and characteristics of SLEDs and photodiodes in the receivers. Such nodes can be deployed in the field where nodes need mobility and exchange information among each other directly, or via an intermediate node. Future research will include design of efficient protocols that can allow information transfer using optical techniques in a mobile environment unfettered by RF interference. Detailed analysis and optimization of the design are part of the ongoing research in our laboratory.

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