Optical Wireless Multi-Spot Diffusing; a MIMO Configuration

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Abstract- **Optical (infrared) wireless communications links offer an attractive solution for indoor applications. To enable terminal mobility and reduce temporal dispersion, we use a configuration known as Multi-Spot-Diffusing (MSD), which is a Multi-Input, Multi-Output (MIMO) architecture. In this configuration, a transmitter generates multiple narrow beams that get uniformly spread over a reflection surface accessible to a service area. A multi-branch receiver with each branch having access to a diffusing spot (generated by transmitter) combines signals on its branches. This scheme creates multiple virtually ideal communications channels between a base station and terminals. This paper considers issues involved in the design of a transmitter-based holographic spot array generator. The generator produces equally-spaced diffusing spots on the room ceiling and/or walls. To overcome power limitation set by eye safety requirements, a receiver optical concentrator is proposed. Furthermore, to improve receiver signal-to-noise ratio, an optical filter that rejects optical noise is needed. Thus, functionally receiver branch optical front-end consists of an optical concentrator and an optical band-pass filter. A single holographic optical element, capable of performing both functions is proposed. Link performance is investigated by providing equivalent link model and comparing probability of error for a bare and a holographic receiver. From performance evaluations, our results show that it is possible to achieve an increase of 11 dB in the SNR and improve power budget by reducing the path loss by over 6 dB.**

I. INTRODUCTION

Optical wireless communications technique is an attractive solution for indoor applications. The links operate on a vast frequency band (of about 300 THz,) so the carrier frequency poses no limitation on the information speed. Also, there are no limits on the bandwidth used by an optical wireless network. Thus, by nature, infrared links can offer an immense capacity, practically only limited by the transceiver performance. Optical frequencies are free and available and there are no regulations regarding this part of the spectrum, worldwide. The short carrier wavelength and large detector area lead to efficient spatial diversity that prevents multi-path fading caused by in-phase cancellations, a phenomenon that typically degrades performance of an unprotected RF link. Optical transmission does not interfere with electronic devices. This makes it more suitable for use in hospitals, airports, factory plants, etc., where RF interference is not permitted. Current technology offers cost- and size-effective IR transmitters and receivers: semiconductor laser diodes, light emitting diodes, and Si photodiodes. Using infrared light instead of radio waves would minimize the health hazard although infrared light is still an electromagnetic radiation. The key difference is that IR is absorbed either by the clothes or by the very thin outer layer of human skin of the uncovered parts of the body. It does not penetrate body depths and cannot interfere with the oscillatory endogenous electrical activities of the living human body. There is no known health hazard provided that eye-safety requirements are satisfied.

In free space optical links, there are two major factors that impose severe restrictions on system design and performance: noisy environment and eye-safety requirements. Daylight coming from windows, incandescent and fluorescent lighting, remote control units, infrared headphones - these are sources of ambient light. Infrared links employ simple intensity modulation with direct detection, so that signal-to-noise ratio is proportional to the square of received power. Hence, only a limited loss of power can be tolerated. This implies that IR links should transmit at a relatively high power. Although the power level can be increased without fear of interference, transmitter power is limited by eye-safety concerns. System design must account for a tight power budget and a very high level of optical noise, caused by natural and artificial light sources.

II. BASIC LINK DESIGNS

Various link designs may be employed in infrared communication systems. Different designs offer solutions to different issues. Each design trades between system complexity, bit rate, coverage range, robustness to shadowing and need of alignment.

Directed line-of-sight or point-to-point infrared wireless links offer one-to-one communications. Such signal transmission is used, for example, in television remote control module. It is power efficient, but is a subject to shadowing. If someone 'shadows' or blocks the narrow transmitter beam, the signal can't get through. This configuration requires alignment of transceiver, which excludes mobility of user.

Non-directed non-line-of-sight transmission [1], which uses a broad “diffuse” beam, suffers less from shadowing but usually forfeits the power efficiency, broadband, and low average error rate values that IR transmission can offer. Signal transmission in diffuse links relies on efficient scattering of infrared light by surfaces painted in light colors. However, this creates delayed optical signals that reach the receiver after several reflections from walls and other objects. The multi-path signal distortion leads to intersymbol interference. Data rates under this phenomenon have never really been all that fast. This architecture provides one-to-many and many-to-one communications, simplicity of operation since does not require aiming, and supports roaming (mobile terminals can be moved anywhere within the office). The major drawbacks here are poor power efficiency and multi-path induced pulse spreading.

As an attempt to combine the mobility of diffuse systems and the power efficiency and high data rate of directed line-of-sight systems, different hybrid schemes have been researched.

In cellular architecture [2], transmitter is mounted on room ceiling and illuminates evenly certain areas with distinct boundaries on a desktop level, thus creating a communication cell. The system performance strongly depends on the degree of directionality of the transmitter. The more directed emission, the higher the power efficiency and the achievable bit rate. However, the more directed transmitter serves smaller number of users because of the physically smaller size of the communication cell. Since the communications rely on existence of clear direct path between the communicating units, any established link is vulnerable to blockage by physical obstruction of the path. In order to cover the office area, several transmitters need to be mounted on the ceiling, thus creating several non-overlapping communications cells.

Tracked architecture [3] is a modification of the classical narrow-beam line-of-sight link. In order to provide mobility, tracking and optical steering is added to maintain signal lock. A base station is mounted on the ceiling and is designed to produce several steerable narrow beams, each providing a single user with a line-of-sight link. In tracked architecture, the link acquisition time can degrade system performance. This is alleviated in a similar solution that uses multi-element transmitter and segmented receiver, so that the coverage area is divided into uniquely addressable cells through angular-spatial mapping.

III. MULTI-SPOT DIFFUSING ARCHITECTURE

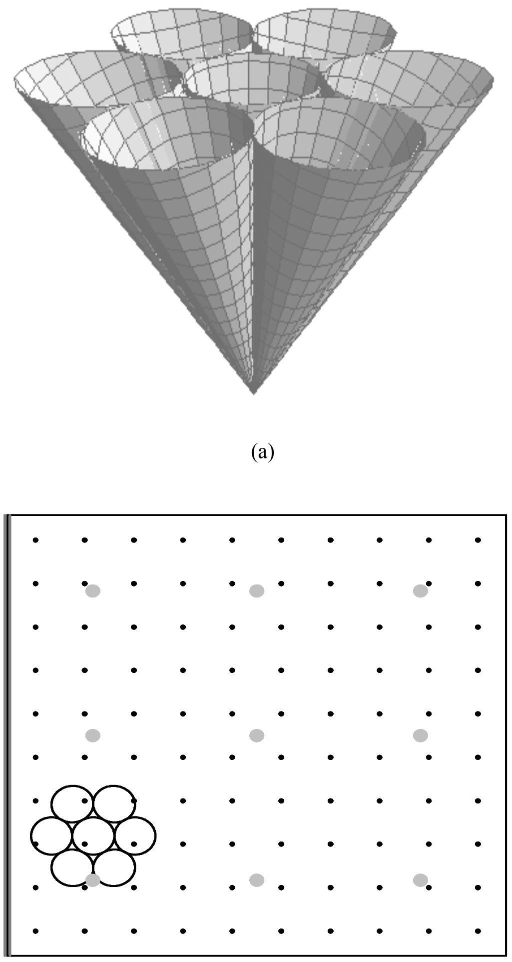
Multi-spot diffusing configuration [4] was designed as a modification to the classical diffuse links. It retains mobility feature of diffuse systems and, by introducing elements of line-of-sight topography, it allows for multi-path distortion-free communications. In MSD, transmitter is placed at a desktop level and the signal power is transmitted in form of multiple narrow beams of equal intensity, with each beam aiming in a pre-specified direction. Such a transmitting scheme produces multiple illuminated areas of small size, called diffusing spots, all of equal power, on the ceiling or walls of a room. Each diffusing spot in this arrangement may be considered as a secondary line-of-sight light source having a Lambertian illumination pattern. A direction-diversity receiver (also known as angle-diversity receiver) that utilizes multiple narrow field-of-view receiving elements is used in order to provide a diversity scheme to substantially reduce the intersymbol interference and for optimal rejection of ambient noise power. Each receiving element is pointed at a different direction in order to ensure uninterrupted communications in case some of the transmitter beams are blocked, as shown on Fig. 1.

With proper joint optimization of receiver and transmitter, MSD links can be made multi-path distortion-free [5]. This is achieved by reducing the receiver branch field-of-view to a value, which ensures that no more than one diffusing spot lies within the branch field-of-view. This way, a good portion of the total optical power can be received by each receiver branch via a single signal path. Then, several virtually ideal communications channels are established between the base station and each portable.

In optical communications, optical subsystems design is definitive and an important issue. In MSD configuration, the entire ceiling of a room has to be covered by a regular grid of diffusing spots in order to ensure a uniform distribution of optical signal and user roaming ability within a communications cell. We have designed a holographic spot-array generator for transmitter pattern shaping [7]. It produces equally- spaced diffusing spots on the room ceiling.

Due to the extremely small feature size of hologram pattern, electron-beam lithography had to be used in the hologram fabrication, in Fig. 2.

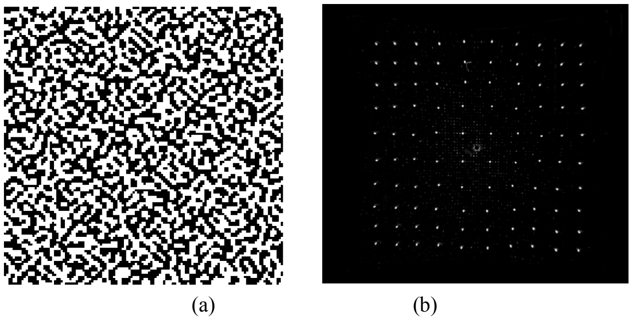
The eye safety requirements limit the power that can be launched via a single diffusing spot. This implies use of an optical concentrator at the receiver. With respect to ambient light, even a weak diffused background light is stronger than the optical signal. To improve the signal-to-noise ratio, an optical filter that would efficiently reject the optical noise is needed. Thus, functionally, receiver branch optical front-end consists of an optical concentrator and an optical bandpass filter. We have designed a single holographic optical element, that is, a holographic parabolic mirror, which performs both concentrating and filtering functions at the same time [8]. Although physically flat (Fig. 3), the holographic mirror concentrates light as conventional parabolic mirrors do, and rejects much of the ambient light due to its spectral selectivity.



(a)

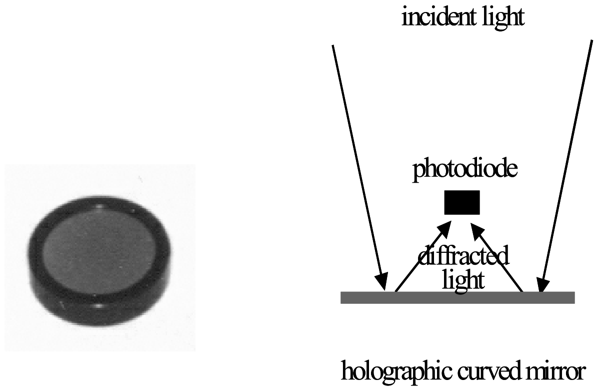
(b)

Fig. 1. (a) Total field-of-view of a 7-branch receiver and (b) areas on the ceiling seen by receiver branches at receiver position (125m x 165m) measured from a room corner. The small black dots represent the diffusing spots grid; the large gray spots represent 100W Tungsten lamps; the left room wall has a large window.



(a) (b)

Fig. 2. Holographic spot-array generator: (a) Hologram pattern (the smallest feature size is 250nm); (b) Far-field illumination pattern.



(a) (b)

Fig. 3. (a) Holographic parabolic mirror. (b) Receiver optical front-end.

IV. CHANNEL CHARACTERISTICS

The characteristics of a communications channel established between a multi-beam transmitter and a multi-branch direction-diversity receiver have been evaluated in [5] and [8]. MSD configuration creates a nearly ideal channel between the transmitter and each *active* branch (one that sees a diffusing spot). The total signal-to-noise ratio is defined by [5]

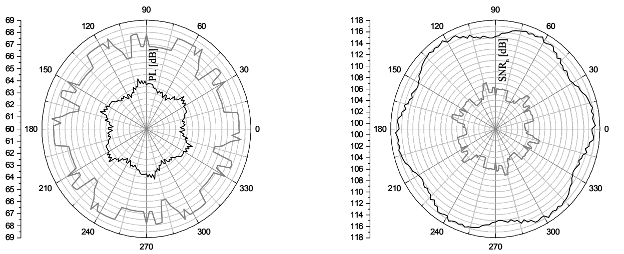
$$SNR = \sum_{j=1}^{7} SNR_j \qquad (1)$$

$$SNR_j = \frac{P^2 r^2 H_j^2(0)}{N_{0j} R_b}, \qquad (2)$$

where P is the optical signal power, r is the receiver responsivity, $H_j(0)$ represents path loss at the j^{th} receiver branch, N_{0j} is the noise variance, and R_b is the information rate.

Because of the uniform distribution of the secondary sources (diffusing spots), the channel characteristics and system performance practically do not depend on the particular receiver position with respect to transmitter. However, the amount of received optical signal and noise power depends strongly on the receiver position and orientation with respect to the diffusing spots grid and the ambient light sources. Even simple rotation of a receiver about its normal may cause a change of more than 2dB in the optical path loss and more than 3dB in the signal-to-noise ratio. As an example, the rotational dependence of the path loss (PL) and the normalized signal-to-noise ratio (SNR_n) at the receiver position (125m x 165m) in a 6m x 6m room as depicted in Fig. 1 (b), are shown in Fig. 4.

The only way to properly describe such a model is to use a statistical approach. A total of 2000 random receiver positions and orientations have been selected and the cumulative distribution functions of the optical signal path loss and SNR_n, i.e., signal-to-noise ratio values, normalized to P^2/R_b, have been obtained. Associated CDFs are shown in Fig. 5, where gray lines correspond to the case of bare receiver and black lines are for the case when a holographic parabolic mirror is employed as a receiver optical front-end.



(a) (b)

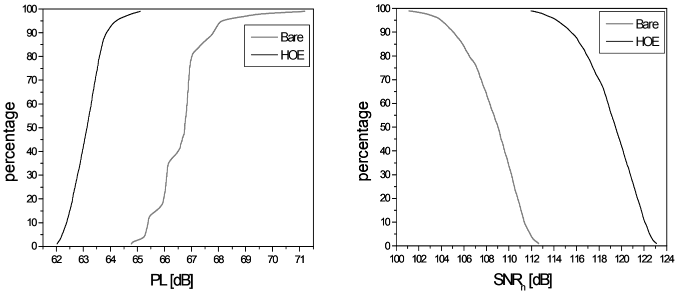
Fig. 4. Rotational dependence of (a) optical signal path loss and (b) the normalized signal-to-noise ratio at receiver position (125m x 165m). Gray lines represent bare receiver; black lines are for receiver equipped with a holographic parabolic mirror.

For the latter, we have used the parameters achieved in the preliminary experiments [9] (signal gain: 6.5dB, optical noise gain: -7.6dB) in order to get an idea about what to expect in terms of signal reception and SNR improvement. Utilization of a holographic receiver front-end improves significantly the system performance: path loss is roughly 6dB lower and the normalized SNR is 11dB larger as compared to the case of a bare receiver. PL is no more than 65dB and SNR_n is no less than 112dB, with a 99% probability (1% outage). This remarkable improvement is due to the improved signal reception and optical noise rejection. Further improvement is expected if a holographic optical element of pure phase type (i.e., having higher diffraction efficiency) is used.

V. LINK PERFORMANCE

In order to better appreciate the improvement brought about by a holographic receiver, we compare the power requirements to achieve a given data rate with bare and holographic receivers. Power requirement is a significant performance measure, since the infrared link has a limited power budget as discussed in Section III.

The link uses intensity modulation with direct detection at the receiver. This requires transmitted signals to have amplitude levels greater than or equal to zero. Data transmission is binary with equally likely ones and zeros. Transmitter filter f(t) has a rectangular pulse shape with an amplitude equal to P. Thus, P_{Total}=P/2 is the average transmitted power over the link. Different paths between transmitter and receiver are represented by H_i and d_i, where H_i, and d_i are the path loss coefficient and delay, respectively. The equivalent link model is shown in Fig. 6. Receiver employs a filter that generates a raised-cosine pulse shape for a rectangular pulse input, i.e., f(t)*g(t)=x_{rc}(t). The receiver compensates for different path lengths by sampling the output of g(t) at a time proportional to the path length. Different branches of receiver experience different noise power according to the branch location and orientation relative to ambient light sources. Since the path loss coefficient and noise power differ at receiver branches, receiver uses maximal-ratio combining to add received signals on different branches. This results in weighting branches with higher signal-to-noise ratio more heavily. Decision circuit decides a 1 was transmitted if the combined signal y[k] exceeds a threshold value V_T and a 0, otherwise.



(a) (b)

Fig. 5. Cumulative distribution of (a) the signal path loss, and (b) the normalized signal-to-noise ratio.

The threshold is equal the average of the expected value of y[k] when 0's and 1's are transmitted and is given by

$$V_T = \frac{\sum_{i=0}^{7} \frac{r^2 P^2 H_i^2}{\sigma_i^2}}{2}. \tag{3}$$

The average probability of error can be expressed as:

$$P_b = P(e|0) \times P(0) + P(e|1) \times P(1)$$

$$= \frac{1}{2} \times P(n_{out} > V_T) + \frac{1}{2} \times P(n_{out} < -V_T\Big) \tag{4}$$

$$= Q\left(\frac{\sum_{i=1}^{7} \frac{r^2 P^2 H_i^2}{\sigma_i^2}}{2\sqrt{\sum_{i=1}^{7} \frac{r^2 P^2 H_i^2}{\sigma_i^2}}} \right) = Q\left(\frac{1}{2} \times \sqrt{\sum_{i=1}^{7} \frac{r^2 P^2 H_i^2}{\sigma_i^2}}\right). \tag{5}$$

Expressed in terms of SNR, the probability of error becomes:

$$P_b = Q\left(\frac{\sqrt{SNR}}{2}\right) \tag{6}$$

Fig. 7 shows the required power versus bit rate for different receivers using the average SNR. The figure shows an improvement of 5.2 dB with the holographic over bare receiver.

Although using average SNR in power calculation gives a measure of required power to achieve performance requirements, a more meaningful measure uses outage calculations. Outage determines the power budget needed to meet the performance in a specified percentage of receiver locations. For an outage of 1%, the link meets the performance criteria at 99% of receiver locations. For this value, power saving of the holographic receiver is equal to 5.4 dB, as shown in Fig. 7.

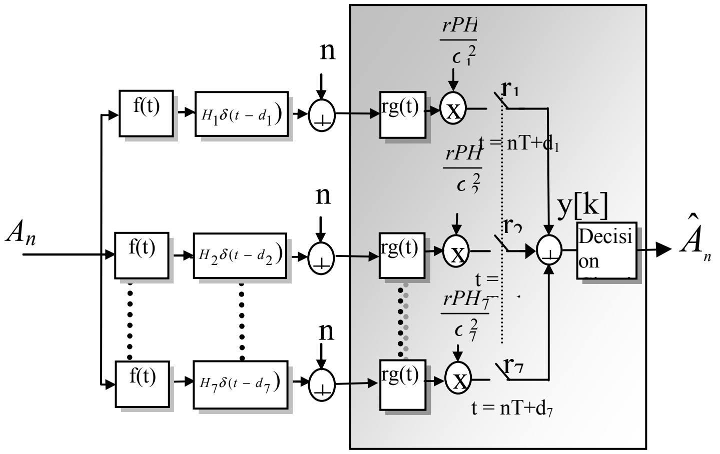


Fig. 6. Equivalent link model, receiver uses MRC to add received signals across its branches.

VI. CONCLUSIONS

Bandwidth available for optical wireless communications is substantially greater than that available for radio communications. The two major IEEE wireless radio-LAN standards (802.11b and 802.11a) operate on 2.4 GHz and 5 GHz frequency bands and offer 11 Mbps and 54 Mbps, respectively. Bluetooth provides an even lower capacity. We have shown that, with proper system design, optical wireless links utilizing multi-spot diffusing architecture are capable of offering significantly higher rates in the order of 100 Mb/s and higher.

MSD links don't suffer from multi-path induced signal distortion. However, the poor power efficiency still remains a major issue in MSD links. It is due to the high path loss, a characteristic feature of all non-line-of-sight links. The use of a holographic receiver front-end reduces the path loss and improves the signal-to-noise ratio, which results in power savings of more than 5dB.

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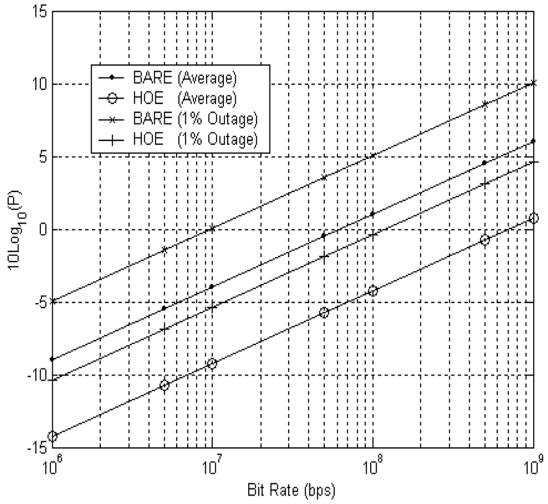

Fig. 7. Required power versus bit rate required by bare and holographic receivers. Average BER is assumed to be 10^{-7}.