Multiple Element Array Antennas for Free Space Optical Communications

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Abstract

In this paper we examine the feasibility of using the 2-dimensional multiple element array antennas for Free Space Optical communications. The problems that arise due to communication using arrays are interference between simultaneous transmissions and misalignment due to vibration. This paper addresses interference caused by simultaneous transmissions by the multiple elements. We model the interference as noise and find the probability of error. We present design guidelines for a interference free operation based on the distance, number of optical transceivers (elements) that can be packed in a given array area, and the achievable aggregate bandwidth.

1 Introduction

Use of multiple element antennas to increase the capacity of a communication channel is well known. It has been demonstrated that capacity can be increased linearly as a function of the number of antennas [3], [2], [4]. Traditionally, Free Space Optical(FSO) communications use a single trasmitting antenna(laser/VCSEL/LED) and a single receiving antenna (a photo-detector) for single channel communication. Current commercial availability of VCSEL arrays and photo-detector arrays can be used to realize parallel multi-channel FSO communications over short distances. This paper examines the feasibility of implementing FSO multiple channels using 2-dimensional arrays.We also present the design choices so as to be able to implement such multi-channel free space optical communication.

Multi-channel operation in optical interconnects has been well studied [5], [6], [7], [8], [1]. The main issues of multi-channel operation are interference between adjacent channels due to finite divergence of the light beam, and misalignment due to vibration. Multi-channel operation is suggested not only for increasing the capacity of the overall system, but also for achieving robustness due to spatial diversity in the case of misalignment. In this paper, we focus on the interference issues and present a simple analysis for rectangular arrays. The results are equally applicable to circular arrays and other forms of 2-dimensional arrays.

This paper is organised as follows. In the next section we describe the notation used and the interference model for the 2-dimensional array antennas. Section 3 discusses the capacity of such 2-dimensional array antennas, and the probability of error due to interference. It also illustrates a few design choices through examples. Section 4 concludes with future directions.

2 Interference Model

The 2-dimensional rectangular arrays for Free Space Optical communications are shown in Figure 1. The circles denote the optical transceivers, i.e., a Laser/LED and a photo-detector. Multiple such transceivers are spaced on the array at a distance S apart. The area of individual transceivers be a. The distance between the two arrays is D. Let θ be

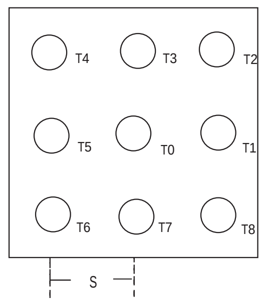

Figure 1: 2-D rectangular array.

the angle associated with each of the transceivers. In practice, it represents the minimum of divergence angle of the transmitter and the angular field of view of the receiver.

In Figure 2, two arrays facing each other are communicating using multiple transceivers. In such a scenario, ideally each of the transceivers on the array is supposed to communicate *only* with the corresponding transceiver on the opposite array. But because of the finite tranceiver angle, the light signals transmitted are not only received by the corresponding transceiver on the opposite array, but also by its neighboring transceivers, causing potential interference. For example, as shown in the Figure 2, consider the transmission from the transceiver T_{02} on array 2 to T_{01} on array 1. Because of the finite Transceiver angle θ, a cone of light of radius r covers the opposite array.

$$r = Dtan(\theta)$$

Thus the light beam coming from T_{02}, is received not only by T_{01}, but also by some of the other transceivers T_{i2} on the array 2 causing interference to their communication. By adjusting the spacing of the transceivers S to be greater that r, interference can be completely avoided. That is, the package density on the arrays, the number of transceivers per unit area, decides the interference caused. Alternatively, the distance between the arrays D, and the transceiver Angle θ can be also be chosen to avoid this interference for shorter ranges.

The total number of transceivers covered by the cone are

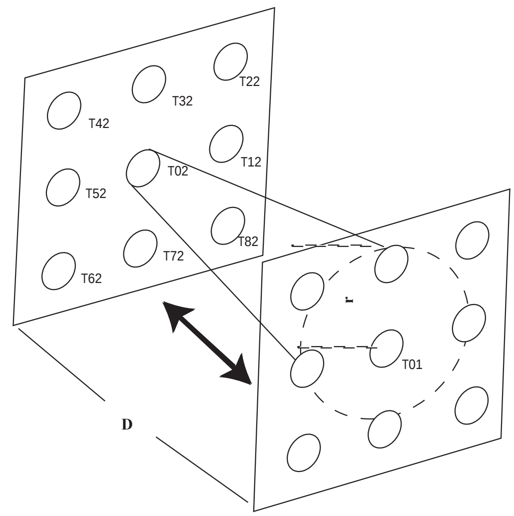

Figure 2: Communication between 2 2-D rectangular arrays illustrating interference due to divergence

$$N = \pi r^2/a$$

Therefore, each transceiver on the array receives power from N transceivers of the opposite array, including the one that is intended to be received. (The edge transceivers receive power from fewer transceivers, but that can be addressed as a special case). Since the radiation is either Gaussian or Lambertian distributed depending on the source used, the power received by the transceiver along the line of sight is different from those that are out of line of sight. The power can be calculated using the angular orientation of the transceivers. Let $\xi(i)$ be the angle at which the i interferer transmitting a power P_i is oriented with respect to the transceiver under consideration. Then the power received from that interferer is given by: $P_i f(\xi(i))$. $f(\xi(i))$ is a function of angle dependent on the light source.

In the present discussion, the noise considered in the system caused purely by interference. Thermal noise and noise due to atmospheric turbulence is not considered for discussion. The focus of this paper is to analyzing the noise caused by interference and the error probability due to the noise. Therefore, noise at a tranceiver is the sum of the power received by all $N-1$ interferers from the opposite array.

Thus, noise n is given by: $n = \sum_{i=1}^{N-1} P_i f(\xi(i))$

For FSO communications, the OOK (On-Off Keying) modulation scheme is used, with two symbols, "0" and "1". When a "0" is transmitted, the transmitter is silent, i.e., no power is transmitted. Whereas when a "1" is transmitted, finite energy is transmitted. A threshold detector is used at the receiver to distinguish between a "0" and "1". Consider the case of arrays with multiple simultaneous transmissions. Consider the situation when a "0" is transmitted in one transmission, and there are "sufficient enough" interfering transmissions, that are trasmitting "1". Then the noise caused by the other transmissions is high enough, the "0" may be detected as "1" by the threshold detector with a finite probability. Let the threshold be γ. Then, when the noise n exceeds this threshold, we have an error, when the data bit sent B_t is a "0".

The probability of error in such a system is given by:

$$P_e = P[(n > \gamma) \cap (B_t = 0)]$$

3 Channel Capacity and Probability of Error

Since the 1 transmitted is always received correctly (in clear weather conditions), error occurs only when a 0 is transmitted. The error is caused assymetrically. The channel corrupted by multi-channle interference can be modeled as a Binary Asymmetric channel. The capacity of such a channel is known to be:

$$C = max_{p_1} H(\bar{p_1}\bar{p_e}) - p_1 H(\bar{p_e})$$

Where, C is the channel capacity, p_1 is the input symbol probability distribution, and p_e is the probability of error.

The plot of the capacity vs the input distribution shown in Figure 3 gives a design insight for the array communication. Since the probability of error is a direct function of interference, which in turn depends on the spacing and the range. we can choose a specific operating point on the capacity curve. In

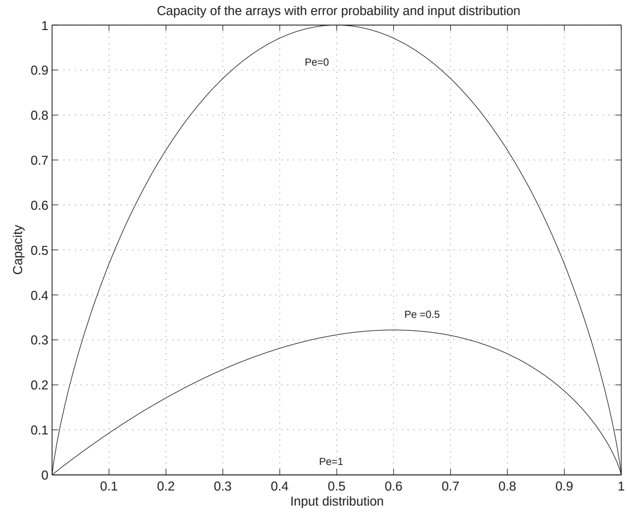

Figure 3: Capacity of the Array system with respect to input distribution and error probability

this multiple channel scenario, we can define a useful design metric that incorporates the important parameters of the system, namely number of channels, capacity of operation of each channel and the range of operation. We designate it as "Bandwith Volume Product". This is simply the product of the number of channels, capacity per channel and the distance over which these channels can be operated.

This is synonymous to the "Bandwidth-Distance" metric of fibre optic link. In the case of a fibre optic link, it's the fibre dispersion that adversly effects the aggregate capacity, where as in the multi-channel Free Space link, it's the interference caused by divergence. The capacity with which each channel can be operated in the multi-channle scenario degrades with increasing distance between arrays.

For a given package density of the array, we can find the number of interferers $N - 1$, and the worst case probability of error for a given package density on the array. An error occurs when the transceiver under consideration transmits a "0" and *any* of the $N - 1$ interfererers transmit a "1". In reality, the power reaching the "desired" receiver from just *one* transmitter may not cause enough noise to exceed the threshold. This worst case probability of error is given by:

$p_e = 1/2[1-(1/2)^{N-1}]$

The package density of the array and the probability of error p_e are closely connected. As the package density increases, for a given divergence and range, the probability of error increases. This decreases the per node capacity in a binary asymmetric channel. A plot of the variation of capacity with package density of the array is given in Figure 4. The plot is given for two ranges, one for 20 meters and the other for 50 meters. As can be seen from the plot, the per channel capacity drops from 1 to .55 for the range 20 meters, when the package density reaches 40 nodes. This is due to the increased interference when the number of nodes that are simulatnepusly transmitting has increased to 40. Where as, when the range is 50 meters, the capacity has fallen to 0.55 for a package density less than 20 nodes per square foot. By identifying a desired operating point on the curve, we can decide the package density that achieves it.

The following examples illustrate how we can choose the package density and the distance D. Examples 1 and 2 show full capacity operation of every node over a specific D. Alternatively, as shown in example 3, the system can be operated at a lower capacity point and get a higher aggregate bandwidth due to multiple operating channels.

Example 1:

- Range 20 meters, Package Density is 40 nodes per Sq. Ft, Divergence is 1mrad, Each node transmitting at 100Mbps
  1. Aggregate Bandwidth: 4Gbps
  2. Bandwidth-Volume Product: 80 Gbps - meter

Example 2:

- Range 50 meters, Package Density is 5 nodes per Sq.Ft,Divergence is 1mrad, Each node transmitting at 100Mbps
  1. Aggregate Bandwidth: 0.1 Gbps
  2. Bandwidth-Volume Product: 5 Gbps - meter

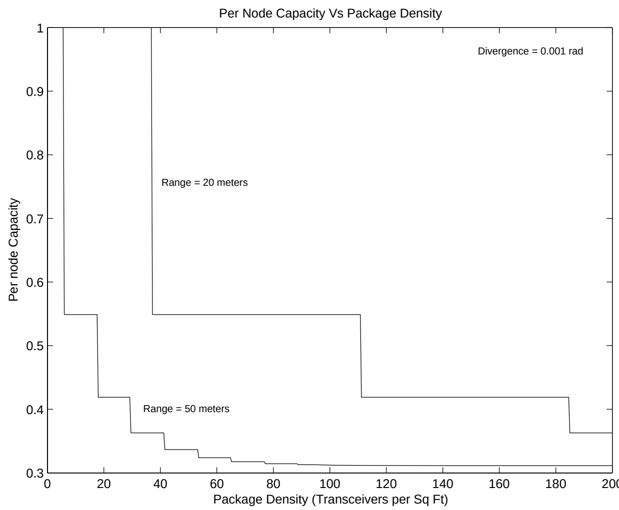

Figure 4: Per channel capacity variation with package density of the array

Example 3:

- Range 50 meters, Package Density is 15 nodes per Sq.Ft, Divergence is 1mrad, Each node transmitting at 100Mbps
  1. Aggregate Bandwidth: 15*100*0.55 = 0.825 Gbps
  2. Bandwidth-Volume Product: 41 Gbps - meter

The above examples demonstrate that we can get very high aggregate bandwidth at shorter ranges. The distance of operation, number of channels should be carefully chosen to achieve the desired capacity. Even if each of the channel is not operated at full capacity, we can still achieve high bit rates due to the presence of multiple simultaneous transmissions.

4 Conclusion and Future Directions

We demonstrated that 2-D arrays give excellent bandwidth performance over short range Free Space Optical communications for good divergence properties of the transceivers. Multiple hops of Free Space

Optical channels can be easily implemented in a LAN environment. For example,in an indoor access network or a campus-wide LAN scenario, we can tremendously increase the bandwidth by using 2-D arrays. To use these arrays over very long distances in outdoors, we need very narrow beams coupled with auto-aligning mechanisms.

The interference of the system can further be reduced by using time multiplexing and coding techniques, there by improving the performace. Finding suitable time multiplexing techniques and codes for varying package density and ranges is an interesting future problem. Alternatively, we can use multiple wavelengths and filters to reduce interference, which again is another interesting research direction.

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