Multi-Element Array Antennas for Free-Space Optical Communication

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***Abstract*— In this paper we examine the feasibility of using 2-dimensional multiple element array antennas for free-space optical communications. Spatial diversity due to multiple antennas on 2-d arrays can increase aggregate link bandwidth. On the other hand, simultaneous transmissions between the elements on the arrays can cause inter-channel interference, reducing the effective bandwidth. We model this inter-channel interference as noise and find the probability of error due to such noise. Based on this error model, we then derive channel capacity estimations. We present design guidelines based on the link range, number of optical transceivers (elements) that can be packed on a given array, and the achievable aggregate bandwidth.**

I. Introduction

The 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 in wireless communications [1], [2], [3]. However, traditionally, free-space optical (FSO) communications use a single transmitting antenna (laser/VCSEL/LED) and a single receiving antenna (a photo-detector) for single channel communication [4].

Multi-element array design for FSO communication is very attractive since it offers high aggregate bandwidth and link robustness due to spatial diversity. As an example, optical transceivers are capable of operating at bandwidths greater than 100 Mbps. With each transceiver operating at a speed of 100 Mbps, a 10×10 array will give 10 Gbps in aggregate capacity. On the other hand, close packaging of transceivers on the arrays is not possible without avoiding interference of optical beams for neighboring transceiver elements. The main issues of multi-channel operation are interference (or cross-talk) between adjacent channels due to finite divergence of the light beam, and misalignment of the array elements due to mechanical vibration.

In this paper,we examine feasibility of implementing multiple FSO channels using 2-dimensional arrays. We also present the design choices so as to be able to practically implement such multi-channel FSO communication. We focus on inter-channel interference issues and present an analysis on the behaviour of the aggregate bandwidth as a function of such interference for rectangular arrays. The results are equally applicable to circular arrays and other forms of 2-dimensional arrays.

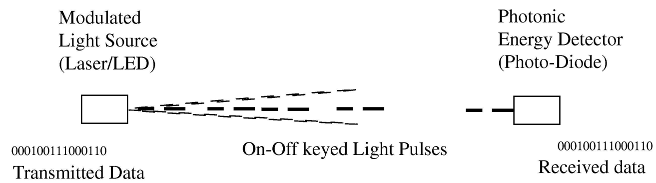

Fig. 1. FSO communication system.

We assume a clear channel free of atmospheric disturbances, and focus only on the noise due to inter-channel interference in array communication. We model the noise due to such interference and the resulting error using a binary asymmetric channel with On-Off keying interms of the link range and array parameters. Based on this interference error model, we proceed to estimating aggregate transmission capacity of the FSO arrays. We try to find optimal packaging density of transceivers on arrays, without sacrificing the aggregate bandwidth, and to implement a more practical array size.

The rest of the paper is organized as follows: In the next section and Section III, we describe briefly an FSO communication system and the notation we use for model derivations respectively. Then, in Section IV we derive the interference model for the 2-dimensional array antennas. Section V 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 VI concludes with directions for future work.

II. System Description

An FSO communication system is shown in Figure 1. The transmitter is a modulated light source, typically a low-powered laser operating in infrared band. The receiver is a photo-detector, and outputs a current proportional to the received light intensity. The receiver is in line of sight of the laser beam from the transmitter.

FSO communication supports duplex connection, therefore both transmitter and receiver are present at both the ends. We call each end an "optical transceiver", which can both transmit and receive at the same time. An optical transceiver can be characterized by the transmitted light intensity I, an angle θ and receiving sensitivity η. The angle θ is the divergence angle of the laser beam. The intensity of the light varies across the

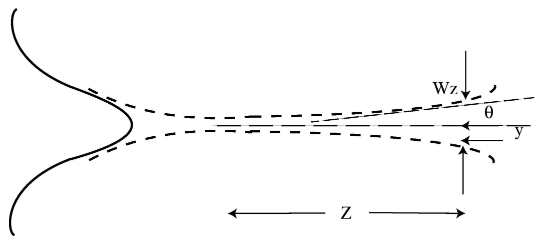

Fig. 2. Laser beam profile.

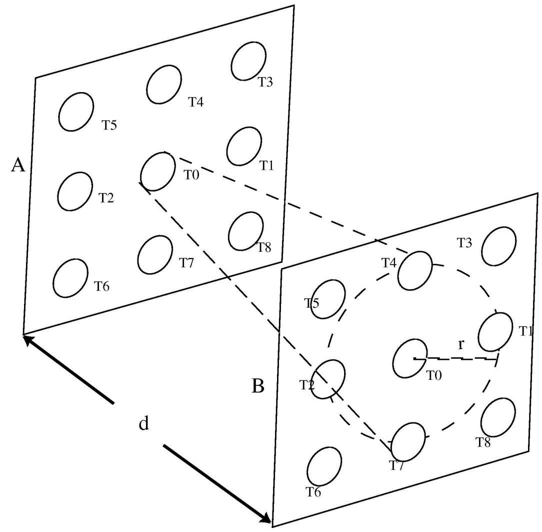

Fig. 3. Proposed array design for FSO communication.

cross section of the light beam [4] following the Gaussian beam profile. The intensity I_Y at a radial distance Y from the axis at a distance Z from the laser is given by:

$$I_Y = I_o e^{-\left(\frac{2Y}{W_z}\right)^2}$$

where I_o is the intensity at the center of the light beam and W_z is the diameter of the laser beam at distance Z. As seen, the intensity of the laser beam falls exponentially across the cross section.

Is On-Off Keying (OOK) digital modulation method the carrier (light beam) is switched on to transmit a *ONE* and switched off to transmit a *ZERO*. At the receiver, the photo-detector operates in a threshold detector mode to receive the signal. If the received light intensity is greater than a preset threshold I_T, then the detector outputs a *ONE* and if the received light intensity is smaller than I_T, the detector outputs a *ZERO*.

III. Two-Dimensional Arrays for FSO Communications

The 2-dimensional array we propose FSO communications is shown in Figure 3. The circles denote the optical transceivers, i.e. a light source (Laser/LED) and a photo-detector. Multiple such transceivers are spaced on the array. The total number of transceivers per unit area on an array is referred to as *package density* ρ.

Two such identical arrays face each other to facilitate communication between the corresponding optical transceivers on the arrays. 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 transceiver angle, the light signals transmitted will diverge by the time they reach the opposite array and they are not only received by the corresponding transceiver on the opposite array, but also by its neighboring transceivers, causing interference.

For example, as shown in Figure 3, consider the transmission from the transceiver T_0 on the array A, T_0^A to T_0 on the array B, T_0^B. For a transmission between the transceivers AT_0 and BT_0, as shown in the figure, the cone from the transceiver AT_0 extending onto the array B defines the field of view of the transceiver. The radius of the cone on the array B is a function of the distance between the two arrays d and the transceiver angle θ as given by:

$$r = d tan(\theta)$$

Because of the finite transceiver angle θ, not only T_0^B is present in T_0^A's field of view, but also four more transceivers T_1^B, T_2^B, T_4^B, and T_7^B. Extending the argument, T_0^B not only receives light from T_0^A, but from all the transceivers in whose field of view T_0^B exists. We call those transceivers as "potential interferers".

Interference at T_0^B can happen if the intensity of light coming from these potential interferers is greater than I_T. Since the intensity of the light beam varies across its cross section, not all the potential interferers can cause cross talk due to their transmissions. Cross talk is caused only when these interferes at a distance "Y" from T_0^A such that

$$I_Y \geq I_T$$

If there are $N \geq 1$ interferers at distance "Y", crosstalk occurs if

$$NI_Y \geq I_T$$

Let us define a distance on the array Y_T, such that

$$I_{Y_T} = I_T$$

So transceivers spaced within $2Y_T$ (one Y_T for each of the adjacent transceivers) are bound to interfere with each other resulting in crosstalk. So the minimum separation between the transceivers on the array should be greater than twice Y_T, so adjacent simultaneous transmissions does not result in crosstalk. Numerically, for arrays at a distance of 100 meters, and with a transceiver angle of θ as 1 mrad, the value of Y_T lies around 40 cms if I_T is set to $\frac{1}{2}I_o$, where I_o is the intensity at the center of the laser beam. This suggests that we cannot place the optical transceivers closely packed in a small area on a compact array, even though with current day technology, we can obtain miniature lasers and photo-detectors.

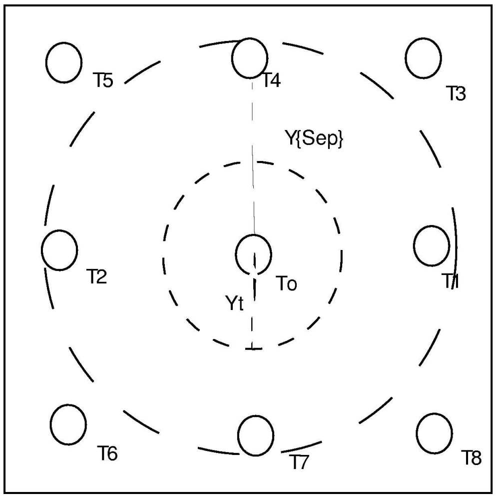

Fig. 4. The circles with radii Y_T and Y_{Sep} on the array.

IV. Interference Model

In a single channel FSO communication system, the received signal quality is limited by Gaussian shot noise following the photo-detector [5]. However, in a multi-channel system like in an array, noise is a combination of the above described AWGN and noise caused by inter-channel interference. Since the AWGN noise is common to all the receivers and can be combated either by increasing the signal power or by using error control codes, the noise contributed only by the inter-channel interference is considered in the remainder of the paper for discussion. In this section, the resulting error due to such noise the its effect on the channel capacity is disussed.

Let us define a packaging density of the transceivers on the array ρ_o that satisfies the minimum spacing $(2Y_T)$ condition to avoid inter-channel interference.

$$\pi {Y_T}^2 \rho_o = 1$$

and for an arbitrary spacing Y_{Sep}

$$\pi {Y_{Sep}}^2 \rho_o \leq N_o$$

$$N_o I_{Y_{Sep}} \leq I_T$$

Interference happens when the package density ρ is greater than the optimal density ρ_o. The total number of transceivers N for a package density ρ within the field of view θ(r) is given by:

$$\begin{aligned} N &= \pi \rho r^2 \\ &= \pi \rho (d tan \theta)^2 \end{aligned} \quad (1)$$

The total number of interferers is $N-1$, as N includes AT_0. These $N-1$ transceivers could have been placed anywhere on the array with in a radial distance of r from AT_0. Interference can happen when a subset of these transceivers transmit at the same time as T_0^A. The probability of that event gives the probability of error resulting due to interference. That is obtained in the following discussion.

Let us assume that these $N-1$ transceivers are distributed to be on J imaginary circles of radii r_J. We can calculate the error probability due to interference interms of each of the J circles as one unit.

The number J is decided by the Y_{Sep} of the array.

$$J = \left\lfloor \frac{r}{Y_{Sep}} \right\rfloor$$

Since the transceivers are uniformly spaced distances Y_{Sep}, the radius of the Jth circle is $r_J = J \cdot Y_{Sep}$. The number of transceivers K_J on the Jth circle is a function of package density ρ of the transceivers on the array. This is given by:

$$K_J = \pi \rho (r_J)^2 - K_{J-1}$$

$$K_o = 1$$

Interference at T_0^B happens only when $K_J > N_o$ and $K_j I_{jY_{Sep}} \geq I_T$, for $j = 1, 2..J$. To understand when exactly interference happens, consider the following cases, for $j = 1, 2, ..J$.

1) T_0^A transmits a 1 and K_j a 1
2) T_0^A transmits a 1 and K_j a 0
3) T_0^A transmits a 0 and K_j a 1
4) T_0^A transmits a 0 and K_j a 0

Interference happens only in $Case3$, since only then T_0^B receives a false threshold at its receiver. In all other cases the recieved light intensity does not cause a false threshold. The probability of error P_e caused by such an event can be expressed as: *the probability that all the K_J transceivers on at least one of the J circles is transmitting a ONE when T_0^A is transmitting a ZERO*.

To formulate P_e, we start with expressing the probability that a transceiver not transmitting a *ONE* as p_0. For a circle j with K_j transceivers, the probability that the circle is not transmitting a *ONE* can be expressed as:

$$P_{j,0} = {p_0}^{K_j}$$

Similarly, the probability that none of the J circles is transmitting a *ONE* can be written as:

$$P_{J,0} = \pi_{j=1}^{J} P_{j,0}$$

Based on this notation, P_e could be written as:

$$\begin{aligned} P_e &= [1 - P_{J,0}]\, p_0 \\ &= \left[1 - \pi_{j=1}^{J} {p_0}^{K_j}\right] p_0 \end{aligned} \quad (2)$$

We assume equal transmission probability for a *ONE* and *ZERO* ($p_0 = 1/2$).

As it can be seen from (2) and the derivation of K_j, the error probability is a function of the package density ρ, the distance between the arrays d and the transceiver angle θ. Figure 5 and Figure 6 show the variation of P_e with d and θ as a function of the package density on the array ρ.

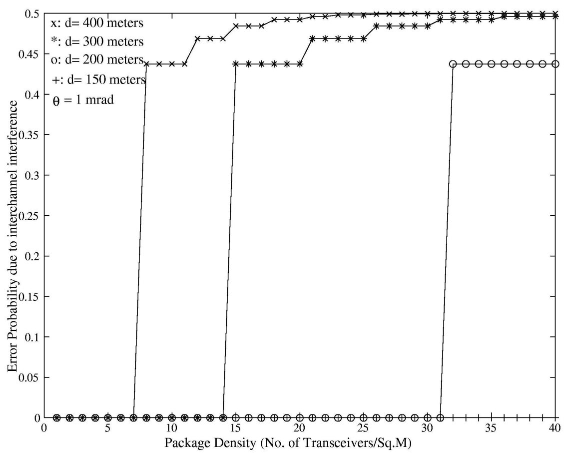

Fig. 5. Error probability variation with package density for various distances.

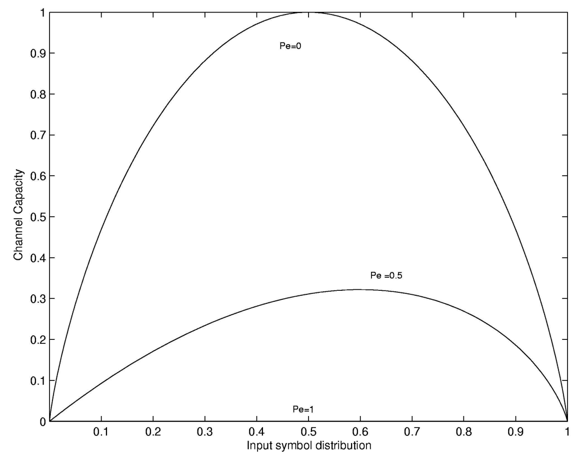

Fig. 7. Capacity of the binary asymmetric channel for the array antennas.

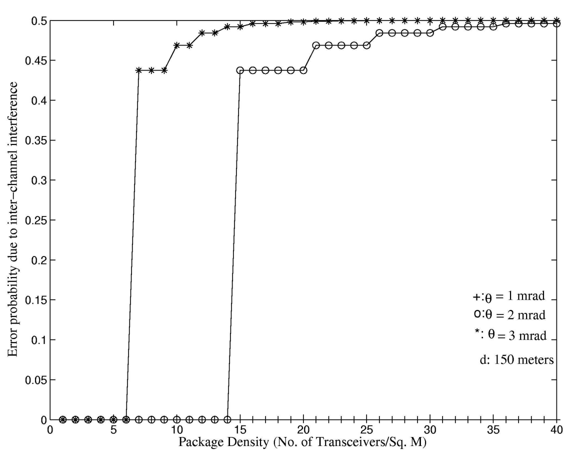

Fig. 6. Error probability variation with package density for various divergence angles.

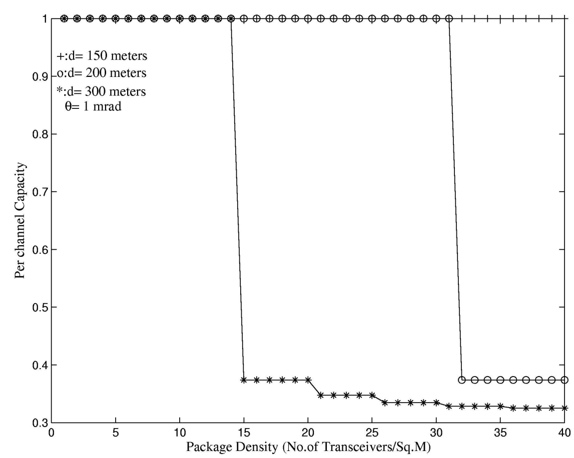

Fig. 8. BAC capacity variation with array package density for various distances.

V. Aggregate Channel Capacity for the Array Transmission

Use of arrays for FSO communication gives the benefit of higher transmission bandwidth due to spatial diversity. Higher package density has a potential for higher aggregate bandwidths, but at the same time causes inter-channel interference. In this section, we look into the question: How is the aggregate channel capacity effected by the error probability due to interference?. We model the array communication channel as a Binary Asymmetric Channel and find the relationship between the capacity of such a channel to the package density of an array.

As described in Section IV, an error in the reception occurs only when T_0^A transmits a *ZERO* and atleast one of the interfereing circles transmits a *ONE*. Since the error is caused asymmetrically, each channel on the array corrupted by inter-channel interference (cross-talk) 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 (*ONE* or *ZERO*) probability distribution, and P_e is the probability of error. A plot of the capacity C versus the input distribution is shown in Figure 7 for various error probabilities.

P_e for the array communication system is given by Equation 2. By fixing a specific operating point on the capacity curve for the arrays, we fix the error probability P_e and in turn a package density, divergence angle and link range.

A. Design Guidelines

In Figure 8 and in Figure 9 the variation of per-channel capacity with package density is illustrated. As the package density increases, the error probability increases and hence the capacity decreases. The specific package density at which the capacity drops from 1 is a function of the distance between the arrays, and the angle of the transceivers and the specific arrangement of the transceivers on the array. The figures demonstrate the behavior of the capacity for a uniformly spaced transceiver configuration.

We can choose the package density such that each channels operates at a full capacity. Alternatively, we choose a package

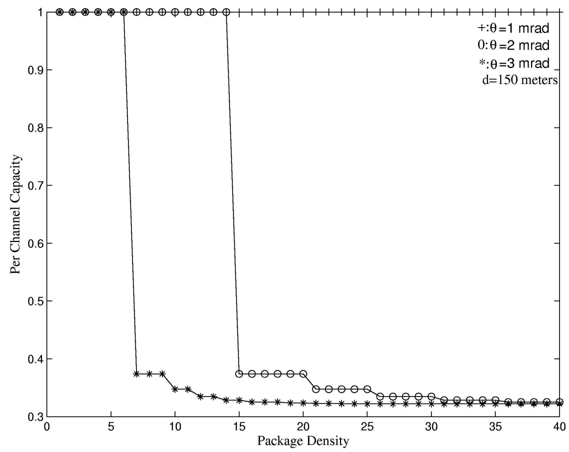

Fig. 9. Channel capacity versus Package density with divergence angle.

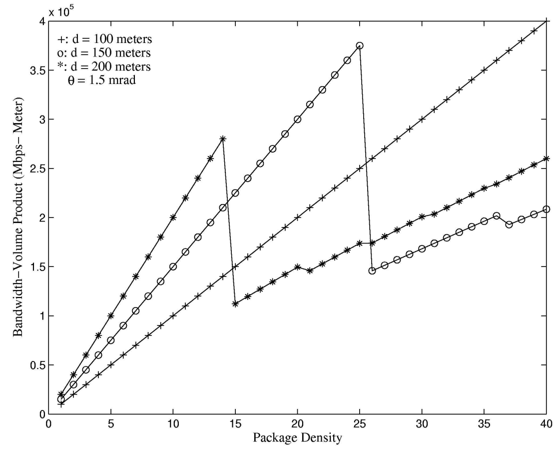

Fig. 10. Bandwidth-volume product (BVP) versus Packaging density with Link Range.

density wherein each channel operates at a lower capacity point and gets a higher aggregate bandwidth due to multiple operating channels. For example, we can choose an array with 5 transceivers, each operating at 100 Mbps each, with an aggregate bandwidth of 0.5 Gbps. Alternatively, we can pack 10 transceivers, each operating at $\frac{3}{4}$'s of its capacity, but with an aggregate bandwidth of 0.75 Gbps. For example as shown in Figure 8, 25 transceivers operating at 0.35^{th} of the capacity offer a higher aggregate bandwidth than 20 transceivers operating at 0.375^{th} of the capacity.

B. Bandwidth-Volume Product (BVP)

We define the performance of an FSO communication channel by three design parameters: (i) number of channels per array, (ii) the capacity of each of the channel in bits per second, and (iii) the distance over which the arrays can communicate with that capacity. We define a useful design metric that incorporates all the above parameters of the system as a product. We designate it as *Bandwidth Volume Product (BVP)*. "Bandwidth" denotes the capacity of a single channel, i.e. the unit of Bandwidth is *Mbps*. "Volume" describes the 2-dimensional nature of the array and the distance over which they can communicate. So, the Volume is simply multiplication of the number of channels on the array and the communication distance, i.e. the unit of the Volume here is *meter*. This means unit of BVP is Mbps-meter.

BVP is synonymous to the "Bandwidth-Distance Product" metric of a fiber-optic link. In the case of a fiber-optic link, it is the fiber dispersion that adversely effects the aggregate capacity, whereas in the multi-channel FSO link, it is the interference.

The advantage of BVP is that it provides an integrated performance evaluation measure to aid the decision process for choosing various parameters (e.g. d, θ) of the multi-element FSO system. 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, one can still achieve high bit rates due to the presence of multiple simultaneous transmissions.

VI. Conclusion and Future Directions

We demonstrated that 2-dimensional arrays give excellent bandwidth performance over short range free-space optical (FSO) communications for good divergence properties of the transceivers. Multiple hops of FSO 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-dimensional arrays. To use these arrays over very long distances outdoors, very narrow beams coupled with auto-aligning mechanisms are needed.

The interference of the system can further be reduced by using time multiplexing and coding techniques, thereby improving the performance. Finding suitable time multiplexing techniques and codes for varying package density and ranges is an interesting future problem. Also, we can use multiple wavelengths and filters to reduce interference, which again is another interesting research direction to improve performance of multi-element FSO systems.

VII. Acknowledgment

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