Optimal Communication Coverage for Free-Space-Optical MANET Building Blocks

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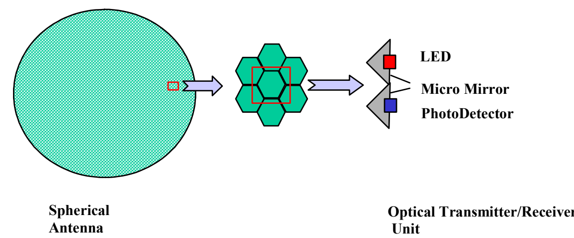
Abstract- **Existence of line of sight (LOS) and alignment between the communicating antennas is one of the key requirements for free-space-optical (FSO) communication. To ensure uninterrupted data flow, auto-aligning transmitter and receiver modules are necessary. We previously proposed [1] a new FSO node design that uses spherical surfaces covered with transmitter and receiver modules for maintaining optical links even when nodes are in relative motion. In this paper, through theoretical modeling, we answer the question of how much coverage can be achieved by a 2-d circular FSO node with the highest possible number of transceivers. The essence of our analysis is to demonstrate scalability of our FSO node designs to longer distances as well as feasibility of denser packaging of transceivers on such nodes.**

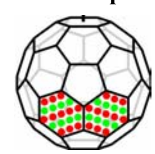
Keywords- **Free Space Optical communication, Auto-Configurable, Angular Diversity.**

I. INTRODUCTION

Optical wireless, also known as free space optics (FSO), is an effective high bandwidth communication technology serving commercial point-to-point links in terrestrial last mile applications and in infrared indoor LANs [6] [2] [10]. FSO has several attractive characteristics like license-free band of operation, dense spatial reuse, low power usage per transmitted bit, and relatively high bandwidth. However, one of the major limitations of FSO is line of sight (LOS) maintenance for continuous data flow. Current FSO equipment is targeted at point-to-point links using high-powered lasers and relatively expensive components used in fiber-optical transmission. Mobile communication using FSO is considered for indoor environments, within a single room, using diffuse optics technology [7]. Due to limited power of a single source that is being diffused to spread in all directions, these techniques are suitable for small distances (typically 10s of meters), but not suitable for longer distances. For outdoors, fixed FSO communication techniques to remedy small vibrations [3], swaying of the buildings have been implemented using mechanical auto-tracking [4] or beam steering [11], and interference [8] and noise [9]. Similarly, for optical interconnects, auto-alignment or wavelength diversity techniques are reported to improve the misalignment tolerances in 2-dimensional arrays [5]. These techniques work only over small ranges (e.g. 1μm – 1 cm) and some of these are cumbersome involving heavy mechanical tracking instruments. Moreover, they are designed to improve the tolerance to movement and vibration but not to handle mobility. Thus, *mobile* FSO communication has not been realized, particularly for ad hoc networking and communication environments.



(a) Tessellated sphere



(b) Honeycombed arrays of transceivers

Figure 1: 3-d spherical FSO systems tessellated with LED+PD pairs.

In order to enable FSO communication in mobile environments, we introduce the concept of spherical FSO node that provides angular diversity and hence LOS in all directions. Figure 1 shows the general concept of spherical surfaces being tessellated with FSO transceivers, i.e. a pair of optical transmitter (e.g. Light Emitting Diode (LED)) and optical receiver (e.g. Photo-Detector (PD)). Such spherical FSO nodes use multiple optical transceivers tessellated on the surface of a sphere. As shown in Figure 1-(b), tradeoffs between spatial reuse and angular diversity can be obtained by constructing the FSO node as honeycombed arrays of transceivers where each array is a cell on the honeycomb. We previously illustrated [1] feasibility of such spherical FSO nodes and demonstrated mobile communication in a two-node proto-type experiment.

In this paper, we show that these FSO node designs can allow very dense packaging and scale to very long communication ranges as well as coverage (e.g. a 1cm radius FSO node with transceivers of radius 0.1cm and source power 32mWatts can cover a total of $2272.68m^2$ in adverse weather and $5230.97m^2$ in clear weather). Our modeling of the proposed spherical FSO node revealed that the source power at transmitters and the visibility have little or no effect on the optimality of the number of transceivers on such structures. Rather, the geometric shape of the FSO node and the divergence angle play the major role, which means that adaptive tuning of the source power based on the actual visibility is possible without having to change the physical number of transceivers on these FSO nodes. This is an important result since it means that optimum number of transceivers is *fixed* for a particular FSO node design.

II. OPTIMUM COMMUNICATION COVERAGE

In spherical FSO nodes tessellated with multiple optical transceivers, there are tradeoffs involving (i) interference (or crosstalk) between the neighboring transceivers, (ii) aggregate coverage area achieved by the FSO node, (iii) packaging density of the optical transceivers, and (iv) communication range. Therefore, higher packaging density provides higher aggregate coverage but also increases the interference of the neighboring transceivers. An important design question is to ask how dense the packaging should be so that highest (or optimal) possible aggregate coverage is achieved without causing interference. Another design tradeoff dimension is the communication range that can be achieved with such densely-packaged FSO nodes. If higher power is fed to the optical transmitters on the node, communication range increases; however, interference also increases at longer distances due to beam divergence.

To investigate the above-mentioned tradeoffs, we present our analysis of the scalability of the angular diversity and spatial reuse provided by a circular shaped FSO node. In particular, we answer the question of how much coverage can be achieved by a *2-d circular FSO node* with the highest possible number of transceivers. To find the optimal number of transceivers maximizing the total coverage of a 2-d circular FSO node, we first develop the model for total coverage area of such a node. Then, we devise an iterative algorithm to find the optimal number of transceivers that maximize the total coverage.

A. Coverage Model

We define the coverage area of an FSO node as the area in which another FSO node can be aligned for communication. Thus, the area, points of which are within the LOS of the FSO node, is called the *coverage area* of the FSO node under consideration. For a 2-d circular FSO node, the total coverage is dependent on the effective coverage area achieved by a single transceiver *C*, and the total number of transceivers *n*. The effective coverage area of a single transceiver can be formulated based on two different possibilities as shown in Figure 2.

Let r be the radius of the circular 2-d FSO node, ρ be the radius of a transceiver, and θ be the divergence angle of a transceiver. We approximate an FSO transceiver's coverage area (which is the vertical projection of a lobe) as the combination of a triangle and a half circle. Let R be the height of the triangle, which means the radius of the half circle is $R\tan\theta$. Also, let τ be the length of the arc in between two neighboring transceivers on the 2-d circular FSO node.

Table 1: MATHEMATICAL NOTATIONS

Symbol	Meaning
n	Number of transceivers on the FSO node
r	Radius of the FSO node (cm)
ρ	Radius of a transmitter (cm)
τ	Arc length between neighbor transceivers (cm)
θ	Divergence angle of a transceiver (Rad)
φ	Angular difference between neighbor transceivers (Rad)
L	Coverage area of a transceiver (cm^2)
C	Effective coverage area of a transceiver (cm^2)
I	Interference area of two neighbor transceivers (cm^2)
R	Height of the triangle in the coverage area of a transceiver (cm)
R_{max}	Maximum range reachable by the FSO node (cm)
P	Transmitter source power (dBm)
S	Sensitivity of the photo-detector receiver (dBm) (assumed -43dBm)
ς	Radius of the receiver (cm)
V	Visibility (km)
q	Particle distribution constant
λ	Optical signal wavelength (nm)
q	Particle distribution constant
x	Side angle of the upper isosceles triangle within the interference area (Rad)
k	Length of the base side of the upper isosceles triangle (cm)
y	Vertex angle seeing the intersecting arc of the interference area (Rad)

Assuming that n transceivers are placed at equal distance gaps on the circular FSO node, and since the diameter of a transceiver is 2ρ:

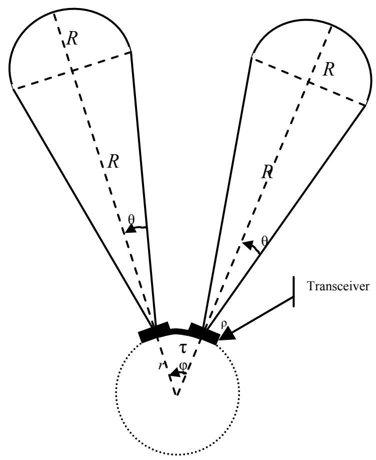
$$\tau = \frac{2\pi r - n2\rho}{n} = 2\left(\frac{\pi r}{n} - \rho\right) \quad (1)$$

From (1), the angular difference φ between two neighboring transceivers can be derived:

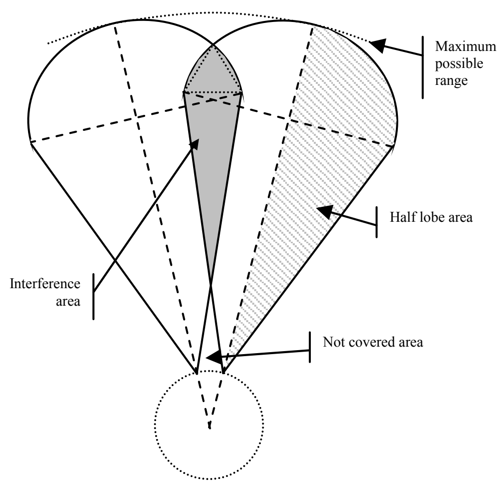
$$\varphi = 360^0 \frac{\tau}{2\pi r} \quad (2)$$

Let L be the coverage area of a single transceiver, which can be derived as:

$$L = R^2 \tan\theta + \frac{1}{2}\pi(R\tan\theta)^2 \quad (3)$$



(a) Case I: Coverage areas of transceivers do not overlap.



(b) Case II: Coverage areas of transceivers overlap.

Figure 2: Coverage area of a 2-d circular FSO node.

For the effective coverage area C of a single transceiver, two cases can happen based on the values of φ, θ, R, and r:

<u>Case I:</u> *Coverage areas of the neighbor transceivers do not overlap, i.e.* $R\tan\theta \le (R+r)\tan(\varphi/2)$. In this case, the effective coverage area is equivalent to the coverage area, i.e. $C = L$.

<u>Case II:</u> *Coverage areas of the neighbor transceivers overlap, i.e.* $R\tan\theta > (R+r)\tan(\varphi/2)$. In this case, the effective coverage area is equivalent to the coverage area excluding the area that interferes with the neighbor transceiver. Let I be the interference area that overlaps with the neighbor transceiver's coverage, then $C = L - I$.

<u>*How to calculate the interference area I? :*</u> As shown in Figure 2-(b), the interference area I is composed of two isosceles triangles and two leftover pies. To find the area I, we need to find the angles x and y, and the length k, as shown in Figure 3. From Figure 3-(a), we can write the following relationships:

$$x + \frac{\varphi}{2} = \frac{180 - y}{2} \tag{4}$$

$$\frac{k}{2\cos x} = 2R\tan\theta\sin\left(\frac{y}{2}\right) \tag{5}$$

From (4) and (5), we find x and y, which means area of the upper isosceles triangle can be found. However, we still need to know the length k, which can be found by angles and lengths of the several triangles in Figure 3-(b):

$$k = 2\frac{R}{\cos\theta}\sin\left(\theta - \frac{\varphi}{2}\right) - 2r\sin\left(\frac{\varphi}{2}\right) \tag{6}$$

<u>*How to calculate the maximum range* $R_{\max}$ *? :*</u> Another important unknown is the maximum range $R_{\max}$ that can be reached by the 2-d FSO node. $R_{\max}$ is dependent on the transmitter's source power P dBm, the receiver's sensitivity S dBm, the radius of the transmitter ρ cm, the radius of the receiver ς cm, the visibility V km, the optical signal wavelength λ nm, and the particle distribution constant q. FSO propagation is affected by both the atmospheric attenuation A_L and the geometric spread A_G, which practically necessitates the source power to be greater than the power lost [10].

Thus, for a conventional photo-detector (PD) sensitivity of S = - 43dB, the following inequality must be satisfied for the PD to detect the optical signal:

$$-(P+43) > A_L + A_G$$

Substituting A_L and A_G leads us to inequality, minimum solution of which is $R_{\max}$ [10]:

$$-\frac{P+43}{10} > \log\left(e^{-\sigma R}\right) + \log\left(\frac{\varsigma}{\rho + 50R\theta}\right)^2 \tag{7}$$

where $\sigma = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q}$.

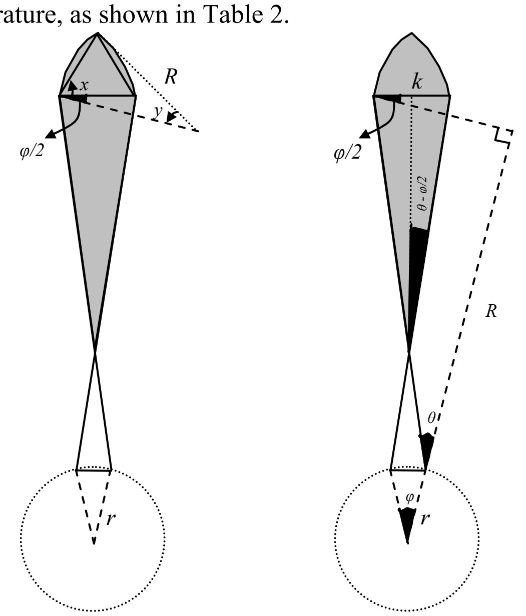
B. Optimal Coverage

For given transmitter source power P, divergence angle θ, and visibility V, optimal number of transceivers that should be placed on the 2-d circular FSO node can differ. We optimize the total effective coverage area nC

of the 2-d circular FSO node, though other metrics can also be chosen. Since *C* is dependent on *P*, θ, *V* and *n*; for given *r* and ρ, the optimization problem can be written as:

$$\max_{\theta,P,V,n}\{nC(\theta,P,V,n)\} \quad (8)$$

such that $0.1mRad \le \theta$, $P \le 32mW$, and $V \le 20{,}200m$. In our search for the best *n*, for a particular FSO node and transceiver size, we varied *P*, θ and *V* based on current FSO technology and literature, as shown in Table 2.



(a) Need the angles *x* and *y*. **(b)** Need the length *k*.

Figure 3: A few key angles and lengths need to be found to find the interference area.

Table 2: PARAMETERS FOR OPTIMIZATION

Parameter	Unit	Value(s)		
		Min	**Max**	**Step**
θ	mRad	0.1	170	5
P	mWatts	4	32	4
V	M	200	20,200	2,000
r	cm	1	20	1
ρ	cm	0.1	*r*/8	0.1

C. Optimal Coverage Results

By applying the approach described in the previous section, we obtained optimal number of transceivers on a 2-d circular FSO node that maximizes the coverage area. Here, we report a subset of our results for the FSO node radius values of 1cm and 5cm for *indoors*, and 20cm for *outdoors*. Similarly, to examine different weather conditions, we varied the visibility *V*. We report a subset of our results for visibility of 0.2km for *adverse*, 6.2km for *normal*, and 20.2km for *clear* weather.

Figure 4 shows the optimal number of transceivers *n* for three FSO node designs (one for indoors, and two for outdoors) for all weather conditions. Note that the optimal n values reported in Figure 4 are valid for all the three weather conditions. So, an interesting observation is that *the source power P and the visibility V have little or no effect on the optimality of n*; rather, the geometric shape of the FSO node and the divergence angle plays the major role. This is a very important result since it means that optimum number of transceivers is *fixed* for a particular FSO node and transceiver size regardless of the visibility and the source power situation. This property of circular or spherical (the property can be shown to be valid for 3-d spheres) *FSO nodes allows adaptive tuning of the source power based on the actual visibility*.

Furthermore, as can be seen from Figure 4, the relative size of the FSO node radius *r* and the transceiver radius ρ determines the shape of the optimal *n* as θ changes. Also, as expected, the optimal *n* reduces as θ decreases, though with steps at specific θ values corresponding to significant changes in the ratio of the interference area with respect to the total coverage area.

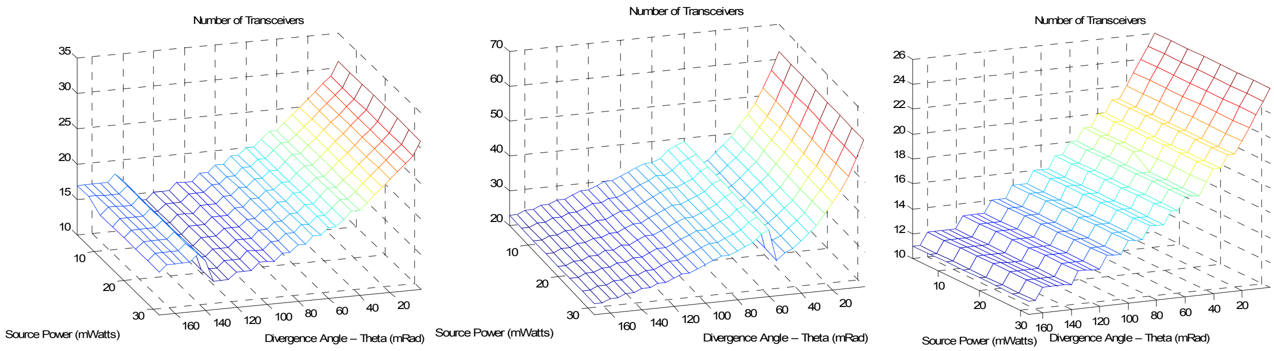
D. Design Recommendations

Value of the communication range, $R_{\max}$, for various FSO node designs is very important as it shows scalability of our circular 2-d FSO node designs for long distances. As it can be seen from Table 3, *the maximum communication range of the node depends solely on the area of the transceiver* for fixed θ and *P*.

Table 3: MAXIMUM COMMUNICATION RANGE IN METERS FOR OPTIMAL FSO NODE DESIGNS WITH θ=170.1mRad AND *P*=32mWatts.

Designs		Weather			Possible Usage
ID	*r*, ρ **(cm)**	**Adverse** *V=0.2km*	**Normal** *V=6.2km*	**Clear** *V=20.2km*	
1	1, 0.1	43.29	64.77	65.69	*Indoor*
2	5, 0.1	43.29	64.77	65.69	*Indoor*
3	5, 0.6	121.23	354.67	382.24	*Outdoor*
4	10, 0.1	43.29	64.77	65.69	*Indoor*
5	10, 0.6	121.23	354.67	382.24	*Outdoor*
6	10, 1.2	162.27	646.88	738.55	*Outdoor*
7	15, 0.1	43.29	64.77	65.69	*Indoor*
8	15, 1	151.00	554.93	622.42	*Outdoor*
9	15, 1.8	188.44	896.78	1072.58	*Outdoor*
10	20, 0.1	43.29	64.77	65.69	*Indoor*
11	20, 1	151.00	554.93	622.42	*Outdoor*
12	20, 2.4	207.82	1115.88	1387.21	*Outdoor*

Table 3 provides the particular designs we investigated. We recommend some of these designs in for



(a) r = 1cm, ρ =0.1cm **(b)** r = 20cm, ρ =1cm **(c)** r = 20cm, ρ =2.4cm

Figure 4: Optimal *n* for three different FSO nodes at all weather conditions: Source power and visibility have little or no effect on the optimality of *n*. The shape of the FSO node and the divergence angle determine the optimality of the total coverage.

indoor usage (i.e. designs #1, #2, #4, #7, and #10) and other for outdoor usage (i.e. designs #3, #5, #6, #8, #9, #11, and #12). Though each design can serve a particular purpose based on the application, we marked the ones that we think fit best to indoor and outdoor usages. For example, designs #7 and #10 would be very good at using as a central hub attached to the ceiling of a crowded room as it can have lots of transceivers on it (i.e. ρ =0.1cm) while communication range can be maintained at the order of 50m. Designs #1 and #2 would perform very well as a small device being attached to laptops or other mobile indoor devices where size of the system is not desired to be large. Similarly, designs #9 and #12 can be used at mobile nodes needing long-range (~1000m) outdoor communication, such as ships and flying objects like helicopters. Designs #6 and #8 seems best for medium-range (~100m) outdoor usage where another communicating node can be found within few hundred meters, as in for the cars or other mobile vehicles in a city. Table 3 also shows that our FSO node designs scale up to 1387.21m as the communication range for outdoors.

III. Summary

We modeled communication coverage and range for a previously proposed scheme for mobile free space optical communications using spherical surfaces tessellated with optical transceivers to obtain spatial reuse as well as angular diversity. We showed, through two-dimensional modeling, that this kind of free-space-optical system designs allow very dense packaging, and can scale to very long communication ranges as well as large coverage. Future work includes issues like optimal transceiver packaging patterns for desired coverage in three-dimensions, and application-specific designs of such systems.

Acknowledgment

This work is funded by NSF grant STI 0230787.

References

[1] J. Akella, M. Yuksel, and S. Kalyanaraman, “Multi-Element Array Antennas for Free-Space-Optical Communication”, *Proceedings of IFIP/IEEE International Conference on Wireless and Optical Communications Networks (WOCN)*, Dubai, United Arab Emirates, March 2005.

[2] S. Acampora and S. V. Krishnamurthy, “A broadband wireless access network based on mesh-connected free-space optical links,” *IEEE Personal Communications* (October 1999), Volume 6, pp. 62 -65.

[3] S. Arnon, S. R. Rotman, and N. S. Kopeika, “Performance limitations of free-space optical communication satellite networks due to vibrations: direct detection digital mode”, *SPIE Optical Engineering* (November 1997), Volume 36, Issue 11, pp. 3148-3157.

[4] E. Bisaillon, D. F. Brosseau, T. Yamamoto, M. Mony, E. Bernier, D. Goodwill, D. V. Plant, and A. G. Kirk, “Free-space optical link with spatial redundancy for misalignment tolerance”, *IEEE Photonics Technology Letters* (February 2002), Volume 14, pp 242 – 244.

[5] G. E. F. Faulkner, D. C. O'Brien, and D. J. Edwards, “A cellular optical wireless system demonstrator”, *IEEE Colloquium on Optical Wireless Communications*, 1999, pp 12/1-12/6.

[6] D. J. T. Heatley, D. R. Wisely, I. Neild, and P. Cochrane, “Optical Wireless: The story so far”, *IEEE Communications* (December 1998), Volume 36, pp. 72 - 74.

[7] J. M. Kahn and J. R. Barry, "Wireless Infrared Communications", *Proceedings of the IEEE* (February 1997), Volume 85, pp. 265-298.

[8] A. J. C. Moreira, R. T. Valadas, and A. M. O. Duarte, “Optical interference produced by artificial light”, *ACM/Kluwer Wireless Networks*, Volume 3, pages 131-140, 1997.

[9] H. Uno, K. Kumatani, H. Okuhata, I. Shrikawa, and T. Chiba, “ASK digital demodulation scheme for noise immune infrared data communication”, *ACM/Kluwer Wireless Networks*, Volume 3, pages 121-129, 1997.

[10] H. Willebrand and B. S. Ghuman, *Free Space Optics* (Sams Pubs, 1st edition, 2001).

[11] Y. E. Yenice and B. G. Evans, “Adaptive beam-size control scheme for ground-to-satellite optical communications”, *SPIE Optical Engineering* (November 1999), Volume 38, Issue 11, pp. 1889-1895.