Optical Antenna: A Three-dimensional Auto-Aligning Building Block for Optical Wireless Ad-hoc Networks

Abstract

Mobile wireless ad-hoc networks and multi-hop fixed-wireless last-mile networks have been primarily based upon radio frequency (RF) technologies. Although optical networking has become popular in the wired networking world, free space optics (FSO) is still a niche technology used to provide only selected point-to-point links, and not as a general-purpose networking technology. Free-space-optics (FSO) has the attractive characteristics of dense spatial reuse, low power usage per transmitted bit, and relatively high bandwidth. However, its primary limitations are the need for the existence of line-of-sight (LOS), explicit alignment of LOS, and reduced transmission quality during adverse weather conditions. In this paper, we propose a novel "optical antenna" design and initial prototype implementation that would make FSO technology more widely applicable (in combination with RF) in mobile ad-hoc and fixed multi-hop wireless scenarios. The central idea is a three-dimensional spherical structure densely populated with Light Emitting Diodes (LEDs) and photodetectors combined with simple electronic LOS auto-aligning circuitry. When two spheres are in LOS, this design allows instantaneous LOS alignment of transceivers. When the spheres move in relation to each other, the design allows rapid handoff of FSO channels without interruption of high-bit-rate communications. Our paper demonstrates preliminary results, and characterizes the key tradeoffs within the subsystems of this design.

1. Introduction

Wireless networking (fixed or mobile multi-hop, or cellular) has been primarily based upon RF-technologies [1][2][3][4]. Though free-space-optics (FSO) is currently used commercially to provide *point-to-point links* in terrestrial applications [5][6][7][8][9][10][11] (and in infrared indoor LANs[1] [12][13]) it is not being considered as a general-purpose *metropolitan area networking* or multi-hop ad-hoc networks technology. There are good reasons for this: FSO communication needs the existence of line-of-sight (LOS), explicit alignment of LOS, and may experience reduced transmission quality during adverse weather conditions [11][14]. Free-space-optics (FSO), on the other hand, has attractive characteristics of dense spatial reuse, low power usage per transmitted bit, and relatively high bandwidth [11][15][16]. In this paper, we investigate the question of how to leverage these powerful advantages of FSO while working around the limitations. In particular, we focus on the problem of line-of-sight auto-acquisition and auto-alignment using electronic/optical methods: essentially a physical layer auto-configuration problem. Note that mechanical and limited electronic auto-tracking methods for a single optical channel are used in current commercial systems [8][9][10][11]: our design is significantly different from these techniques. In addition, we focus on using very cheap components (LEDs instead of lasers) to allow efficient spatial integration of transceivers for dense spectrum reuse and low system cost.

Based upon the above considerations, we propose a novel 3-dimensional spherical structure ("*optical antenna*") that is densely populated with LEDs and photodetectors, combined with simple electronic LOS auto-aligning circuitry (**Figure 1**). When two such *spheres* are in LOS, this design allows instantaneous LOS alignment of the *transceivers*. When the spheres move in relation to each other, the design allows rapid handoff of FSO channels without interruption of high-bit-rate communications (**Figure 2**). This structure will allow uninterrupted, ultra-high-speed operation even in high velocity sway (eg: 120 mph, range over 100s of meters) or even mobile conditions. We report on preliminary results with our auto-alignment implementation. We also propose a 2-dimensional array of optical channels that offers dense spatial reuse of bandwidth (**Figure 3**). Hybrids of the above 2-d and 3-d designs are possible (eg: an auto-aligning 2-d array with hemispheres for each FSO channel). We envision a future where *millions* of such auto-aligning FSO channels can be integrated on small 2&3-dimensional structures with standard photolithography techniques, offering *terabit* aggregate bandwidths powered off a *battery pack*.

2. Potential Applications of Proposed FSO Systems

We believe that solving the auto-alignment using electronic/optical methods is the key to wider applicability of FSO. The ultra-low power, low size/weight, low cost of such FSO structures will allow novel applications in last-mile networks (in combination with RF WLAN [17][18][19], and WMAN technologies[20] [11]), and ultra-high-bandwidth *mobile ad-hoc*

[1] Infra-red LAN relies on wide-angle transmission, reflections from walls and processing, in contrast to other FSO techniques

networks (eg: [1][2][3][4]). Since the size and weight of these structures are expected to be very small, it is possible to mount such systems on ad-hoc infrastructures with heavy sway potential and possibly no fixed-power source (eg: balloons, treetops, lampposts, poles on chimneys, moving vehicles etc). For example, even a simple set of auto-aligning free-space-optical repeaters with low-cost RF backup [19] could be used in last-mile networks; more complex intelligence could be placed at "electronic-hops" which may be separated by tens of FSO repeater hops. Another interesting application area is *sensor* networks where LOS may be present at least intermittently, and very low power budget per transmitted bit property could change the fundamental tradeoffs between computation and communication.

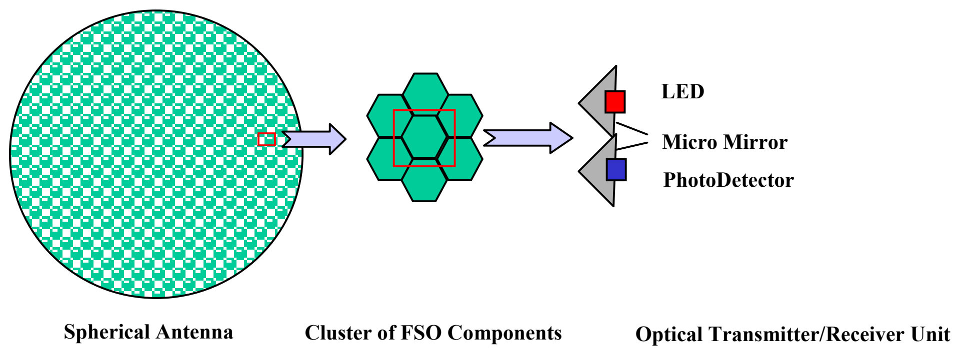

Figure 1: Optical Antenna: 3-d Honeycomb Structure

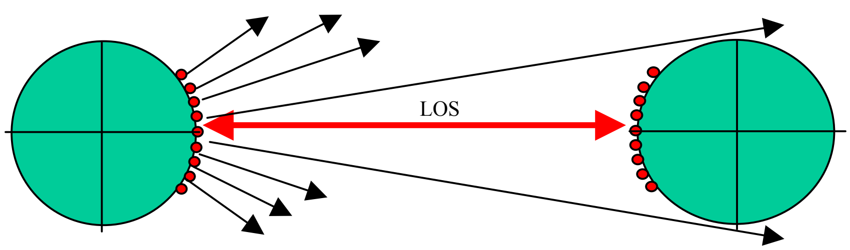

Figure 2: LOS Detection Using the Spherical FSO Transceiver Array

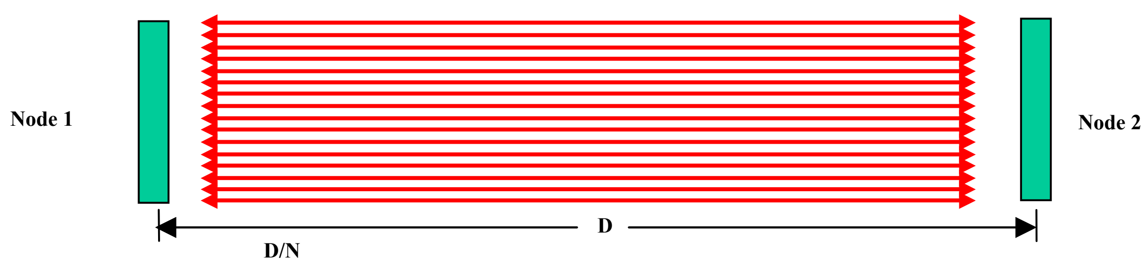

Figure 3: Two-dimensional FSO Transceiver Array for Dense Spatial Bandwidth Re-use

2.1. Comparison of Radio Frequency (RF) and Free-Space-Optics (FSO) Communications

Free space optics (FSO) has several advantages over conventional RF communication technology. FSO is *license-free* since the FCC does not regulate above 300 GHz. Moreover, optical spectrum region is huge and transceivers (LEDs, lasers, photo-detectors) are available today cheaply and in large volumes. High-brightness LED technology is being rapidly developed in the context of solid-state lighting (see [21]). Far-infrared spectrum has attractive propagation characteristics, and LEDs and detectors that could operate without cooling in this region are being actively developed**.** FSO stands to gain from these trends, in addition to leveraging the developments in wired optical systems [24]. Another key benefit of FSO is that *interference issues* in optical wireless are minor and can be easily rejected at the hardware level [11]. This stands in stark contrast to RF that is prone to interference and needs additional computational complexity (signal processing) to combat it. These benefits when combined with the *high directionality and small dispersion* of FSO (compared to RF), leads to enormous potential for *spatial bandwidth reuse*. Within the optical spectrum band, *wavelength division multiplexing* is also possible for additional gain in bit rate. The ultimate limits of the bandwidth gains with spatial integration are unknown (unlike fiber-optical distance-bandwidth tradeoffs that are well studied [15])

Attempts to achieve spatial reuse with phased array structures are well known in the RF world. Recent work has leveraged multi-path propagation to offer multiple spatial channels possible using smart antenna and space-time processing techniques (eg: see [24][25][26]). Though such RF can operate in non-LOS conditions, it cannot match the *high degree* of integration and number of spatial channels possible using FSO when LOS is available. For example, we believe that a small 1 ft x 1 ft array (smaller than a laptop screen) can allow the integration of more than 1000 pairs of transceivers with the current lithographic techniques. With each transceiver pair operating at 100 Mbps, this system would offer an aggregate capacity of 100 Gbps! No RF technology can match this performance; practical expectations of RF techniques with smart antenna techniques in the 5 GHz unlicensed spectrum top off at about 1-5 Gbps. Moreover, RF with spatial arrays (especially in unlicensed bands like 5 GHz) requires placement of complex, high-speed, mixed signal electronics (eg: MIMO algorithms like Lucent's BLAST (eg: [26][27]) that would make the unit operate at higher power levels and would be far more expensive. It is interesting to note that today's laser-based FSO techniques could be extended to form spatial arrays, but such equipment would be very costly and demands high-power. Moreover, such laser-based equipment would not have the form factor, weight and power characteristics to be mounted on ad-hoc infrastructures like balloons, treetops etc. LEDs are more amenable to dense spatial integration, have longer life than lasers, and fewer eye-safety regulations[28].

Ad-hoc networks are *infrastructure-less* wireless networks formed and operated on a fully distributed basis. With RF-technologies, a well-known fundamental limit on the capacity of ad-hoc networks has been enunciated by Gupta and Kumar[2] and subsequent work by Li et al [3] have shown that real ad-hoc networks using 802.11 fall well below the theoretical limit (though Grossglauser and Tse have shown capacity improvement with mobility[4]). In other words, it is well known that the per-user capacity of RF-based ad-hoc networks is fundamentally *interference-limited*. FSO-based multi-hop networks should not face such a fundamental capacity limit because free space optics is *not* interference-limited.

3. Terrestrial FSO Systems Today

Current FSO equipment is targeted at point-to-point links (though some preliminary multi-hop proposals exist [7][29]). Free space optical networking companies (eg: Terabeam [9], Optical Access [8], Light Pointe [10]) have several hundreds of FSO deployments offering links of up to 1Gbps for maximum distances of about 3 km. They use high-powered lasers and relatively expensive components used in fiber-optical transmission. The focus is to form a single primary beam (and some backup beams) with limited spatial re-use/redundancy using multi-laser systems [11]. A dominant objective is to push the limits of the distance for which the FSO beam can go, and to improve link availability during poor conditions (8 km in good conditions & up to 3 km in poor conditions have been reported [14]). In our work, we do not push the distance limits: our targets are for 0.5-1 km since we rely on a multi-hop architecture. Our objective is to solve the LOS alignment problem and enable mobility in FOS systems with our proposed design for the optical antenna. In addition, the reduced geometric dispersion due to shorter distance aids cleaner handoffs of FSO channels for mobility, and allows denser spatial packing of transceivers.

Alignment of LOS is a critical issue in FSO communications. To understand this, assume a $1/e^2$ beam divergence, a tolerance of 2 milli-radians with the links perfectly aligned at installation. A 1 milli-radian building motion would incur a loss of link margin of about 8.6 dB. Even if the link stayed up during this excursion, system performance would be degraded by 8.6 dB from the initially specified margin. This means that for a typical carrier-grade link of 200 m, in the absence of tracking the system can withstand about 43dB/km *less* atmospheric attenuation than the initial design. For calibration, heavy rain can induce about 17–40 dB/km of attenuation, so a system that is designed to handle heavy rain could be brought down in a severe storm.

Currently installed commercial FSO systems have low alignment tolerances and alignment is usually done manually [11] using aids like telescopes, and a rigid mounting is expected. Lasers in the 1550nm band are preferred due to superior propagation characteristics in this band and due to the higher power budget available in lasing[11][14]. Feedback-based auto-alignment that uses a mixture of electronic and mechanical techniques is usually available at higher cost [8][11]. But, a simpler solution used is to simply make the conical optical beam wider at transmission: even with sway, the receiver would remain in the sender's beam. This solution requires higher transmission power. With 1micron divergence, at a distance of one kilometer from the laser, due to geometric dispersion [11], the diameter of the beam is about one meter on a self-aligning system and can be three to six meters on a non-self aligning system.

Dependency on the line of sight between the sender and the receiver imposes a lot of restriction on the mobility of both. The current commercial systems are installed inside a room behind a window and are carefully aligned. Any misalignment or beam wandering will lead to total loss of signal. There are several solutions proposed in literature based on spatial diversity and diffuse light sources and tracking etc [8][9] [10][11][16]. The tolerances given by the spatial diversity methods are usually very small and they hardly can provide any practical mobility. The diffuse system ranges are very limited, usually they are used within a single room [6].

4. Component Choices: Lasers vs. HB-LEDs

We leverage high-brightness LEDs (HBLEDs) [22][23] instead of lasers in our design. Current generation of HBLEDs (and newer resonant-cavity (RC-) LEDs [21]) offer an order-of-magnitude increase in intensity compared to regular LEDs [21]. LEDs can be internally modulated at rates up to 2Gbps [15], though there is a tradeoff with higher brightness (modulation rates up to 100 MHz possible, see **Figure 4**). Unlike the case of fiber optics, the lack of coherence and larger spectral width in LEDs is less of an issue in free-space because the refractive index (RI) of air is close to 1 (fiber has RI of about 1.5 leading to significant dispersion and inter-symbol-interference with LEDs). Moreover, the use of visible spectrum as apposed to infra-red spectrum, allows more power output from LEDs with narrower spectral widths. This enables usage of higher modulation bandwidths (up to 100 MHz) with average powers of the order of 10mW (resulting in 2-5 times increase in distance between the transmitter and receiver, even though the atmospheric windows in visible spectrum are worse than IR-spectrum).

Lasers have superior directionality (low divergence) that helps the beam go long distance with lower geometric dispersion [11]. LEDs on the other hand, typically are highly divergent, though currently LEDs with good directional properties are becoming available (RC-LEDs) [21]. The divergence can be managed to some extent with parabolic micro-mirrors or micro-lens packaging. We propose to live with these limitations due to the other advantages of LEDs. In particular, lasers do not allow high-density spatial integration because of their bulkiness and high power requirements [15]. LEDs do not have these issues. Also lasers suffer from catastrophic failures, whereas LEDs offer higher lifetimes (~ 10 years) and fail gradually over sometime [15]. Recently, wireless communications using high speed LEDs have been reported [30] and several optimizations to their setup is possible for higher bandwidth operation.

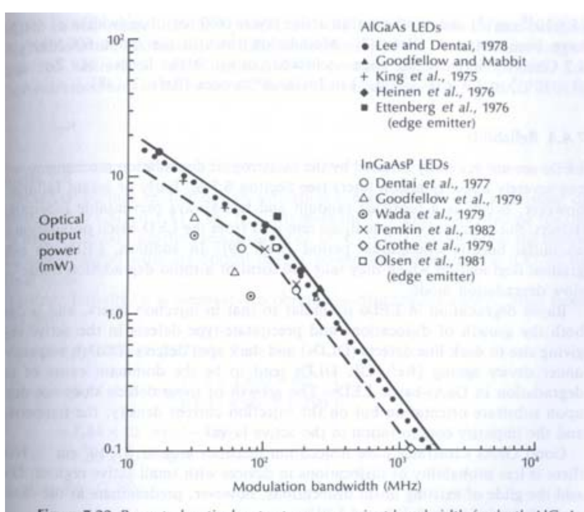

Figure 7.22 Reported optical output power against bandwidth for both AlGaAs and InGaAsP LEDs [Refs. 43, 44]. Best results for AlGaAs devices (solid line). These AlGaAs LED results shifted to a wavelength of 1.3 μm (dotted line). Best results for InGaAsP devices (dashed line).

Figure 4: Modulation Rate vs. Output Power Tradeoffs in HBLEDs

5. Spherical Antenna and LOS Auto-Alignment Description:

The spherical design with dense transceiver integration (**Figures 1, 2, 5**) is motivated by the fact that the "lobe" pattern in FSO is similar to its geometric shape, i.e., with a spherical shape, omni-direction transmission and LOS auto-discovery is possible. Irrespective of the orientation or position of the antenna, two spherical antennas owing to their geometrical shape, will always find a LOS between them. LOS can be instantly discovered using frequent pilot sequences transmitted in multiple directions. Our initial prototype (**Figure 5**) is built using a hollow sphere (obtained from Radio Shack). We installed LED/Photo-detector pairs using universal mounting sockets. These LEDs are then wired to an embedded controller. The controller board processes the signals from photo-detectors (PDs), auto-aligns the LOS using simple circuitry, and then associates a logical electronic data channel (eg: USB or Ethernet output) to the appropriately LOS-aligned physical FSO channel(s). In general, the board could support multiple logical data channels that could be sent along different physical FSO channels simultaneously.

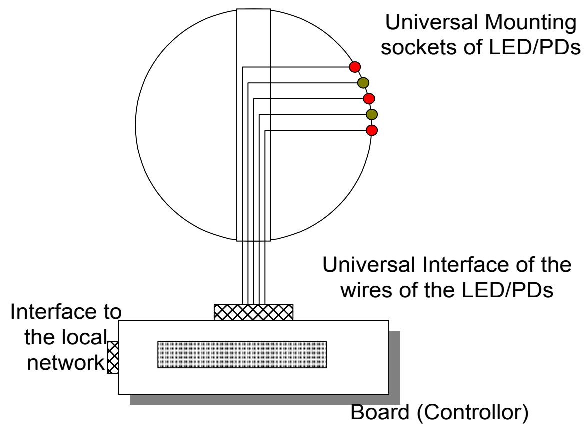

Figure 5: Current Design of Optical Antenna

5.1 Preliminary Auto-Alignment Circuit Design

We now describe two simple auto-alignment circuit designs that we have implemented for the optical antenna shown in **Figure 5**. To simplify the discussion, we consider only a pair of adjacent transceivers. When two transceivers are in line-of-sight (LOS), we would like them to instantly discover LOS and switch over the logical data stream to the LED/PD pair that is aligned. The first design is called a "feedback" design and the second is called an "OR-gate" design.

The feedback design is illustrated in **Figure 6**. The design consists of adjacent units of transceiver packages. Each transceiver package contains a transmitter-receiver pair (i.e. each box A or B1 or B2 in **Figure 6** has both an LED and PD). The design leverages the natural flow of data (AC signal in **Figure 6**) to perform the LOS auto-discovery in this example (in general, pilot signals would be sent in various directions to acquire LOS initially). When the packages A and B1 happen to be in LOS and aligned, the data signal from B1 is received at A (on the top B1-to-A channel). Transceiver-A has an AC-to-DC converter (to measure the RMS signal level), and it simply sends this DC signal back to transceiver-B1 (through the AND-gate) on the bottom channel. This fed-back signal on the bottom part of A-to-B1 channel indicates a "lock" on line-of-sight (LOS). Now this signal gates continued data transmission from B1-to-A. If the feedback signal is not received, the data is not gated in the top B1-to-A channel.

The circuit elements used are very simple. Transceiver-A includes an OP-AMP, an AC to DC Converter and an AND-gate; transceiver-B includes an OP-AMP, an OR-gate linked to a switch and an AND-gate. When the two transceivers are aligned, triggered by the switch, signal is sent from B1 to A. Then A converts the received AC signal to a DC feedback signal and sends it back to B1. By controlling the AND-gate, B1 can continuously send signal to A. If package A moves such that it is now aligned with package B2, the AC-signal that is flowing to B2 as well will now trigger a LOS auto-acquisition as described above. We have tested this design for short distances (15 ft) in the laboratory. Note that once LOS is detected, additional stateful authentication or authorization may be performed at a remote site (after several OEO hops using standard protocols like DHCP).

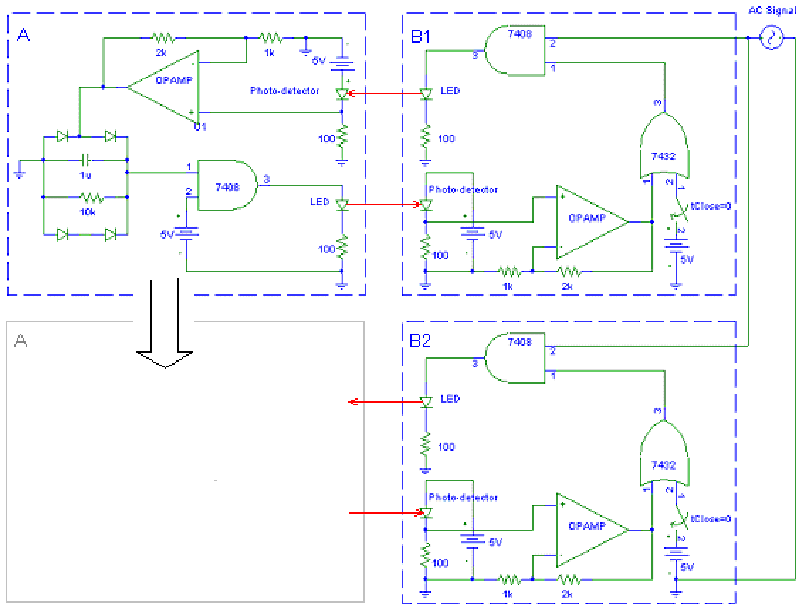

Figure 6: Simplified "Feedback" Design for Automatic LOS Discovery and Alignment

Due to the divergence of the beam, it may be possible for multiple adjacent packages to be simultaneously aligned with channel A. This can be mitigated by having a simple collimator at the receiver. For example a small micro-pipe or pin-hole that rejects non-aligned signals [11] may be used.

The second, more simplistic design (**Figure 7**), uses an open-loop method with simple OR-gates at the receiver. The signals from the photo-detectors, on the receiver, are collected by a cascaded series of OR Gates. Assume that the source sends synchronized data signals in all directions and that the receiving "optical antenna" is in LOS. Different PDs may receive the signal with different intensities. Assuming that the curvature of the sphere does not vary rapidly and that only a few PDs pick up the signal, the cascaded OR circuit will pick up the strongest signal. We have tested this design for short distances (15 ft) in the laboratory. Obviously, this design is a higher-powered design and does not admit spatial re-use because the sender does not know where the receiver is. Our purpose of developing this design is to potentially combine aspects of this with the earlier design, after one or more transceiver packages have acquired LOS.

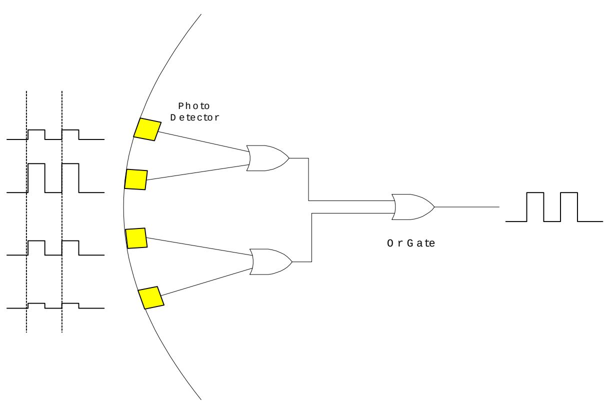

Figure 7: Open-Loop OR-gate Design For LOS-Discovery (Op-Amps, Filters omitted for simplicity).

6. Discussion and Future Work

The initial validation work presented here is quite preliminary, but the proposed concept of auto-alignment and rapid electronic handoffs of FSO channels using a simple feedback-based appears to be powerful. Even our simplistic validation suggests that LOS auto-discovery can be combined with spatial diversity and bandwidth re-use. We intend to rapidly construct further prototypes and deploy it in outdoor environments. There are clearly several challenges ahead that merit investigation. We summarize a few issues below.

The bit-error-rates (BER) of the spherical antenna is defined by the factors like the HB-LED chosen, LED packaging and collimation, power-per-transmitted bit, wavelength(s) used, maximum distance targeted, maximum bit-rate, atmospheric attenuation effects, and probability of LOS loss due to temporary obstacles (eg: when used by a troop of soldiers moving in a wooded area). Structural characteristics such as the *density* of packaging transceivers and the *size* of the sphere also would affect performance and spatial diversity gains.

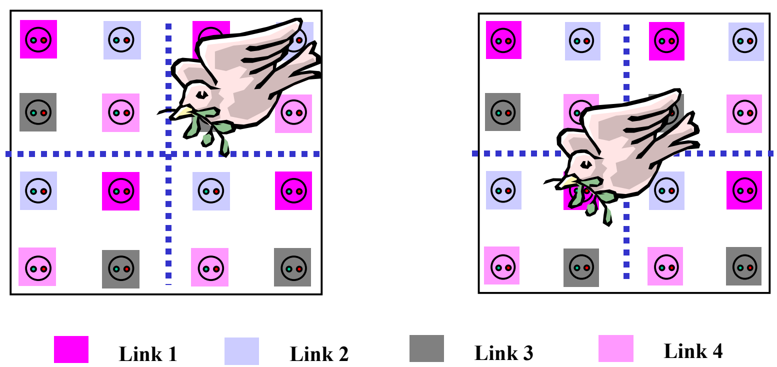

Figure 8: Spatial Error Coding to Protect against Temporary Obstacles

The spatial structures also naturally suggest the leverage of space diversity to protect the links from temporary obstacles such as passing birds etc. For example, **Figure 8** shows a simple 4x4 FSO array supporting 4 *logical* links mapped to 16 *physical* links. Here a simple Gray-coded set-partition scheme is used to allocate the physical LOS links to fewer logical links to obtain space diversity. As illustrated, although the flying bird may temporarily block LOS for a few physical links in both scenarios above, all 4 *logical* links can survive given the additional LOS (physical links) still available in the array. Since we plan to have several (10-100) optical 2d array-repeater hops before introducing the electronics for error resilience, we need to consider the fact that error characteristics would be additive over each optical wireless hop.

In summary, we envision a future where *millions* of such auto-aligning FSO channels can be integrated on small 2-d and 3-d structures with standard photolithography techniques, offering *terabit* aggregate bandwidths powered off a *battery pack*. Designs that enable the use of photolithography using next generation far-infrared LEDs (that are 0.1-0.2mm in size) is a topic of future study.

Bibliography

[1] IETF, "Mobile Ad-hoc Networks (MANET) Working Group", http://www.ietf.org/html.charters/manet-charter.html

[2] P. Gupta and P. R. Kumar, "The Capacity of Wireless Networks," *IEEE Transactions on Information Theory,* vol. IT-46, no. 2, pp. 388-404, March 2000.

[3] J. Li, C. Blake, D.S.J. De Couto, H.I. Lee, and R. Morris, "Capacity of Ad Hoc Wireless Networks," *Proceedings of the 7th ACM International Conference on Mobile Computing and Networking (MobiCom '01),* Rome, Italy, July 2001.

[4] M. Grossglauser and D. Tse, "Mobility Increases the Capacity of Ad-hoc Wireless Networks," *IEEE INFOCOM 2001*, Anchorage, Alaska, April 2001.

[5] X. Zhu, and J.M. Kahn, “Free-Space Optical Communication through Atmospheric Turbulence Channels”, *IEEE Transactions on Communications*, April 2002.
[6] D.J.T. Heatley, et al. “Optical Wireless: The story so far*”, IEEE Communications*, Vol.36, pp. 72 -74, 79-82, Dec. 1998.
[7] A.S. Acampora, et al., “A broadband wireless access network based on mesh-connected free-space optical links,*” IEEE Personal Communications*, Vol. 6, pp. 62 -65, Oct. 1999.
[8] Optical Access Inc., http://www.opticalaccess.com/news-white-papers.shtml
[9] Terabeam Inc., http://www.terabeam.com/
[10] Lightpointe Inc., http://www.lightpointe.com/
[11] H. Willebrand, B.S.Ghuman, “Free Space Optics,” *Sams Pubs, 1st edition*, December 15, 2001.
[12] J.M. Kahn and J.R. Barry, "Wireless Infrared Communications", *Proc. of the IEEE*, vol. 85, pp. 265-298, February 1997.
[13] W. Hirt, M. Hassner and N. Heise, “IrDA-VFIr (16 Mb/s): Modulation Code and System Design,” *IEEE Personal Communications*, February 2001, pp 58-71.
[14] I. I. Kim, B.McArthur, and E. Korevaar, “Comparison of laser beam propagation at 785 nm and 1550 nm in fog and haze for optical wireless communications,” http://www.opticalaccess.com/news-white-papers.shtml
[15] B.E.A. Saleh, M.C. Teich, “Fundamentals of Photonics,” Wiley-Interscience, 1 edition, 1991.
[16] S. G. Lambert and W. L. Casey, “Laser Communications in Space,” *Artech House*, Boston, MA, 1995.
[17] IEEE, “ IEEE 802.11a Wireless Local Area Network standard,” 1999, http://standards.ieee.org/getieee802/
[18] IEEE, “ IEEE 802.11b Wireless Local Area Network standard,” 1999, http://standards.ieee.org/getieee802/
[19] M.S. Gast, “802.11 Wireless Networks: The Definitive Guide,” O'Reilly & Associates, 1st edition, April 2002.
[20] IEEE, “IEEE 802.16-2001, IEEE Local and Metropolitan Area Networks--Part 16 --Standard Air Interface for Fixed Broadband Wireless Access Systems,” December 2001, http://standards.ieee.org/getieee802/
[21] F. Shubert, Light-Emitting-Diodes-dot-org, http://www.rpi.edu/~schubert//Light-Emitting-Diodes-dot-org/
[22] Uniroyal Optoelectronics, “Market Outlook and Product Performance Requirements for Nitride-Based LEDs,” *White Paper*, http://www.uniroyalopto.com/whitepapers/ba1.html
[23] Agilent LEDDesignCenter,http://www.semiconductor.agilent.com/cgi-bin/morpheus/home/home.jsp?pSection=LED
[24] R. Ramaswami, K. Sivarajan, “Optical Networks: A Practical Perspective,” Morgan Kaufmann Publishers, 2nd edition, 2001.
[25] A. Paulraj and D. Gesbert, “Smart antennas for mobile communications*,”* Chapter in *Wiley Encyclopedia on Electrical and Electronics Engineering*, Ed. J. Webster, Wiley, 1998.
[26] B. Pattan, “Robust Modulation Methods and Smart Antennas in Wireless Communications” *Prentice Hall*, *1st edition,* 1999.
[27] P. W. Wolniansky, G. J. Foschini, G. D. Golden, R. A. Valenzuela, V-BLAST: An Architecture for Realizing Very High Data Rates Over the Rich-Scattering Wireless Channel, invited paper, *Proc. ISSSE-98*, Pisa, Italy, Sept. 29, 1998. http://www.bell-labs.com/project/blast/
[28] International Electrotechnical Commission, “CEI/IEC825-1: Safety of Laser Products,” 1993. Also see: J. D. Rancourt, *Optical Thin Films*. Macmillan, 1987.
[29] J. Zhang, “Proposal of Free Space Optical Mesh Network Architecture for Broadband Access”, *IEEE International Conference on Communications,* Vol. 4, pp. 2142-2145, April 2002.
[30] G. Pang, et al., “Optical Wireless based on High Brightness Visible LEDs”, *IEEE Industry Applications Conference,* Vol. 3, pp. 1693 -1699, 1999.