Free Space Optics: A Viable Last-Mile Solution

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INTRODUCTION

The telecommunications deregulation of 1996 has paved the way for a massive expansion in global telecommunication networks over the past few years (Ref. 1). Starting with the growth of long-haul WANs (wide area networks), followed by a recent interest in MANs (metropolitan area networks), there has been a tremendous explosion in bandwidth demand and requirements. For the end user to access and utilize the broad array of services made available through these developments, network designers must provide a flexible and cost-effective solution for the "last mile" between the LANs (local area networks), MANs, or WANs.

This paper explores FSO (free space optics) as an access technology in the last mile of MANs. Merrill Lynch predicts FSO will grow into a $2 billion market by 2005 (Ref. 4). According to the report, "the drivers for this market are a mere 5 to 6 percent penetration of fiber to business buildings; cost effective solution versus RF (radio frequency) or fiber; and significant capacity which can only be matched by a physical fiber link." This paper describes FSO technology, its capabilities and limitations. The paper addresses the case for FSO within the last-mile broadband wireless arena and outlines core applications and deployment architectures to suit the needs of a specific business type. The paper also provides an insight into the Bechtel FSO initiative, with performance results.

BACKGROUND

FSO is an optical technology that allows transmission of video, voice, and data through the air using lasers or LEDs (light emitting diodes). Instead of the pulses of light being contained within a glass fiber, they are transmitted in a narrow beam through the atmosphere. FSO has been in use for over 30 years, well before fiber-optic cables were thought of as a transport medium. Several manufacturers claim that their FSO systems can carry full-duplex data at gigabit-per-second rates over metropolitan distances of a few city blocks to a few kilometers.

FSO is not a disruptive technology; it is more of an enabling technology that would help serve the growing and seemingly insatiable bandwidth demand in the marketplace. This form of delivering services can have compelling economic advantages.

THE CASE FOR FSO

According to various statistics, nearly 90 percent of the buildings in the U.S. have no direct access to fiber, yet more than 75 percent of businesses are within 1 mile of the fiber backbone. To link a building with fiber costs anywhere between $100,000 and $200,000, and often involves a provisioning delay of 4 months to a year. FSO can provide a cost-effective last-mile alternative to other broadband wireless initiatives like LMDS (local multipoint distribution service) and MMDS (multichannel multipoint distribution service). According to most FSO vendors, an FSO link can be up and running within 2 to 3 days at one-third to one-tenth the cost of fiber (Ref. 2). Currently, FSO systems can achieve OC-3 (155 Mbps) to OC-12 (622 Mbps) speeds, although some vendors advertise gigabit Ethernet speeds.

FSO DRIVERS

Figure 1.
FSO Drivers (Ref. 4)

The growing need for FSO is driven by various factors (Ref. 4), some of which are discussed below. (See **Figure 1.**)

Market Drivers

Market drivers that make a case for FSO are as follows:

- **Growth of Internet Users:** According to various statistics, the number of Internet users is projected to grow to approximately 796 million by the end of 2005. This fuels the need to provide larger bandwidth to the end user.
- **E-Commerce:** B-to-B (business-to-business) activities within e-commerce are prime users of bandwidth. Service providers are forced to allocate high bandwidth at the edge of the network.
- **LMDS/MMDS:** Given the high costs involved in acquiring spectrum, and time to build LMDS/MMDS networks, FSO proves to be a viable option. Reference 5 compares LMDS and FSO systems.
- **3G/4G Buildout:** FSO can be used as a transport vehicle for backhauling voice and data traffic for mobile wireless networks in certain situations. The eventual buildout of 3G/4G networks would mean additional marketing opportunity for FSO systems. More information on mobile wireless infrastructure deployment via FSO can be found in Ref. 6.

Economic Drivers

Cost is an important factor in the broadband wireless access segment. A cost comparison of FSO and various established broadband wireless access technologies has been summarized in **Table 1**. The figure of merit (cost/Mbps/month) determines the economic feasibility of an access technology. At nearly $4/Mbps/month, FSO is clearly the cost-effective solution. Economic drivers for FSO include:

- **Service Provisioning:** FSO systems require less than one-fifth of the capital expenditure of comparable ground-based fiber-optic technologies (Ref. 7). Installation can be done in a few days, and systems often can be placed in offices behind windows, thus not requiring roof rights. A service provider can start generating revenue while a fiber-based competitor is still seeking municipal rights to dig up streets to lay cable. Using available network management tools, service providers can efficiently and cost-effectively perform provisioning from a central location through a point-and-click GUI (graphical user interface), thus eliminating time-consuming and expensive "truck-rolls."
- **Scalability and Flexibility:** With a scalable bandwidth between 10 Mbps and 2.5 Gbps, FSO systems offer a broad range of speeds to support the growth of new services.
- **Revenue Generation for Service Providers:** FSO systems would include new SLA (service level agreements), QoS (quality of service) enhancements, dedicated wavelengths to the end user, and bandwidth on demand, without significant hardware changes or additions. This would enable service providers to rapidly introduce new upgrades. To suggest a business case for wireless carriers, a cost-benefit projection was generated by fSONA Communications Corp., Canada (Ref. 8), for a base station hotel application wherein the assumptions listed in **Table 2** were made.

Table 1. Comparison of Established Broadband Wireless Access Technologies and Free Space Optics Systems (Ref. 3)

Access Medium	Speed (Mbps)	Monthly Cost ($)	Cost/Mbps/ Month
Dial-up	0.056	20	357
Satellite (DBS)	0.4	50	125
Cable modem	1.5	50	33
DSL (minimum)	0.144	49	340
DSL (maximum)	8	1200	150
T-1	1.54	350	195
T-3	45	3000	67
RF (Median price with six vendors)	155	1250	8
FSO (SONAbeam™ 155-M)	155	555	4

Table 2. Assumptions for Projected Cash Position (Ref. 8)

Assumption	Parameter
No. of buildings	5
No. of customers per building	50
Avg. revenue per customer per year	$24,000
Connectivity	$100,000
Fiber equipment (DWDM)	$10,000
FSO equipment	$30,000
Customer penetration, Year 1	10%
Customer penetration, Year 2	15%
Customer penetration, Year 3	20%

The projected cash position (ongoing operational cash flow) for creating a standalone traditional cell site as compared to using FSO is illustrated in **Figure 2**. According to a study by ADC Telecommunications Corporation and fSONA (Ref 17), it can be seen that the FSO model has a 14-month ROI (return on investment), as opposed to 34 months for the traditional model

Service Drivers

FSO is suitable for various service classes/types. The following are various service drivers for FSO systems:

- **Need to Eliminate the Metropolitan Area Gap:** FSO helps in situations where the core network and the edge have conflicting technologies. With DWDM (dense wavelength division multiplexing) and wavelengths of 1550 nm, service providers will be able to integrate metropolitan area optical networks with FSO networks (Ref. 4).

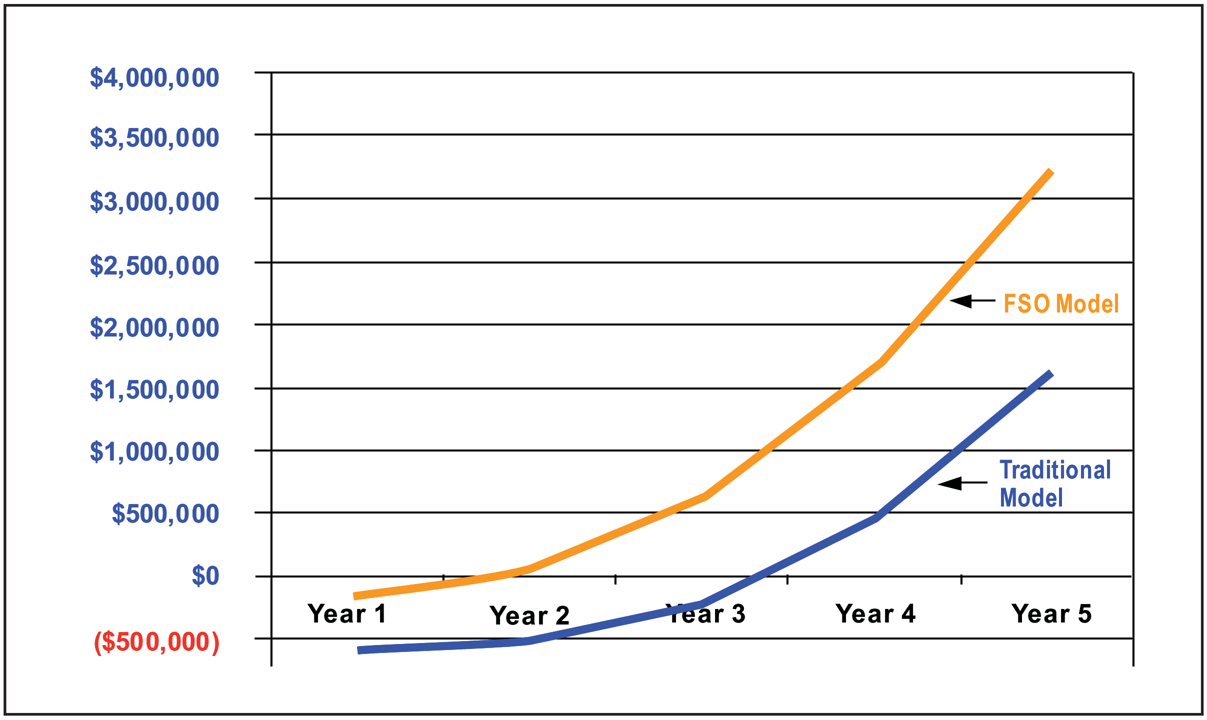

Figure 2. Projected Cash Position for Traditional (Fiber) and FSO Systems (Ref. 8)

- **Adaptive Bandwidth Provisioning:** Service providers would need to employ adaptive bandwidth provisioning to cope with unpredictable traffic patterns and changing customer needs. With FSO, a network can be extended as the customers are located. This would mean less capital expenditure than wireline networks, allowing the operator to have a committed revenue system before incurring infrastructure costs (Ref. 4).

FSO APPLICATIONS

FSO has several applications in providing connectivity between the network core and the network edge. FSO is capable of meeting the demands of several different roles in metropolitan area access networks. Common applications include:

- **Telecommunication Network Extensions:** FSO can be deployed to extend an existing metropolitan area ring or to connect it to new networks.
- **Enterprise:** The flexibility of FSO allows it to be deployed in many enterprise applications such as

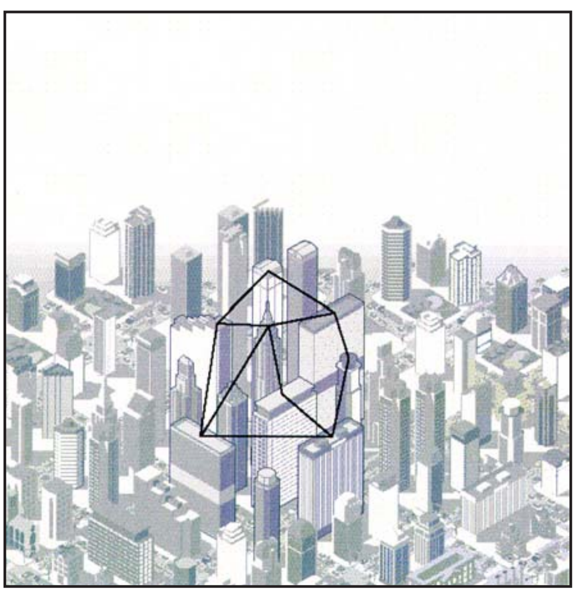

Figure 3. Mesh Network Architecture (Ref. 10)

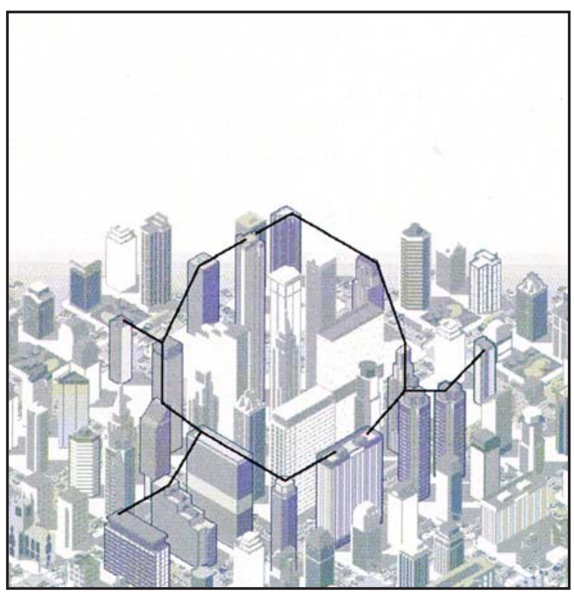

Figure 4. Ring-and-Spur Network Architecture (Ref. 10)

LAN-to-LAN connectivity, storage area networks, and intra-campus connectivity.

- **Last-Mile Connectivity:** These links can be configured as PTP (point-to-point), PMP (point-to-multipoint), ring, or mesh connections, for the last mile.
- **Fiber Complement:** FSO may be deployed as a redundant link to back up fiber. Instead of deploying a second fiber link, operators could opt to deploy an FSO system as the redundant link. However, this is limited to the last mile.
- **Access:** FSO can be deployed in access applications such as gigabit Ethernet access.
- **Backhaul:** FSO can be used for backhaul, typically as part of a link to support LMDS or cellular backhaul, as well as gigabit Ethernet "off-net," to transport network backhaul (Ref. 9) with limitations in range.
- **DWDM Services:** With the integration of WDM (wavelength division multiplexing) in FSO systems, independent players can aim to build their own fiber rings with partial ownership of the ring using FSO.

DEPLOYMENT STRATEGIES

FSO systems can be designed and engineered to work in any network topology, including mesh, PMP, PTP, and ring with spurs. This gives metropolitan area service providers the freedom to rapidly build and extend networks that deliver fiber-optic speeds to today's customers.

Mesh Architecture

A mesh network is composed of a series of interconnected nodes with some degree of redundancy (see **Figure 3**). In such a network, every node is connected to every other node, either directly or by a series of hops. The level of redundancy in the network determines the level of connectedness in the network. Thus, the higher the number of nodes, the better the system. Mesh networks offer high reliability with easy node addition.

Ring-and-Spur Architecture

Ring-and-spur architecture is commonly used in metropolitan area networks. Here, the backbone is made of high-speed rings based on either fiber or FSO (see **Figure 4**). In a ring architecture, sub-rings can be connected together, usually through a layer 3 router. Customers that are part of a ring are protected from a single point of failure in the network. When a customer is added to the network, a link is established from a node in the backbone ring, termed a spur. If the customer wants to pay for redundancy, then the spur can be connected back to another node in the network, forming a new ring. In this way, the service provider essentially provides a level or redundancy to the end-user based on their requirement for availability of service (Ref. 8, 9).

Point-to-Multipoint Architecture

As shown in **Figure 5**, a single node serves as an originator and multiple links emanate from it (Ref. 10). The most effective method is to connect each FSO link into a layer 2 or 3 device located in a building closet. Then the links are fiber coupled to the switch or router and placed at arbitrary locations either on the building rooftop or in an interior room or office therein. Attempts have been made to sectorize the optical beam to serve more than one customer at a time from a single node, as done in LMDS systems, but this architecture is restricted by power limitations imposed by regulatory authorities like the CDRH (Center for Devices and Radiological Health) and International Electrotechnical Commission (Standard IEC60825-1).

Multiple PTP Architecture

Multiple PTP architecture is suitable in cases where it is desirable to create an extensive link path that exceeds the product range limit or the recommended weather-constrained distance for an optical link. This is illustrated in **Figure 6**.

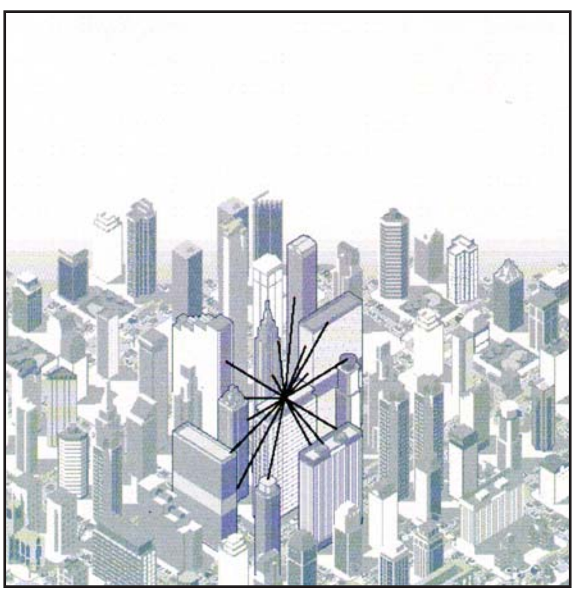

Figure 5. PMP Network Architecture (Ref. 10)

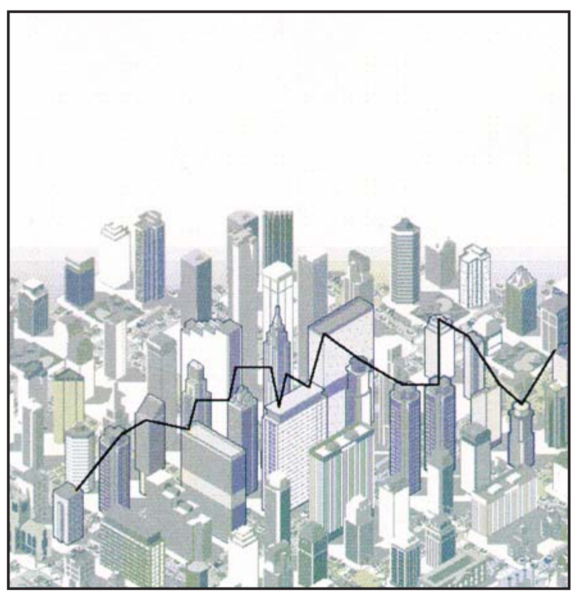

Figure 6. Multiple-PTP Network Architecture (Ref. 10)

FSO CHALLENGES

An FSO medium is subject to outside disturbances, unlike fiber, which is a closed system. Unpredictable atmospheric changes can seriously affect the performance of an FSO system. FSO is an LOS (line-of-sight) technology like millimeter wave radio systems. The following issues limit the performance of an FSO system:

- **Weather:** Weather is the most important factor affecting the performance of an FSO system. Severe conditions of rain or snow can result in link outages; however, fog can also cause signal attenuation. **Table 3** summarizes the effect of environmental attenuation on FSO systems. The results are based on field trials conducted by fSONA (Ref. 11) on their 155 Mbps product, SONAbeam™ 155-M, which works at 1550 nm.

  Fog interference, more formally known as "Mie scattering," is a major challenge for FSO communication. Fog is a vapor composed of water droplets having a diameter of a few hundred microns, which can modify light characteristics or completely stop the passage of light due to a combination of absorption, scattering, and reflection. In areas of frequent, heavy fog, it is often necessary to choose 1550 nm lasers, because of the higher power transmitted at that wavelength. The solution to achieving carrier-class availability in foggy conditions is to have shorter range (200–500 m) and add redundancies.
- **Physical Obstructions:** Birds and growth in foliage can obstruct the beam, but this tends to cause only temporary (intermittent and semi-permanent) interruptions, and transmission can be quickly resumed. In situations of interruptions, the bandwidth is lowered to maintain connectivity, although with a low data rate.
- **Scintillation:** Scintillation can be best defined as the temporal and spatial variations in light intensity caused by atmospheric turbulence. Such turbulence is caused by wind and temperature gradients that create pockets of air with rapidly varying densities and, therefore, fast-changing indices of optical refraction. FSO systems can deal with scintillation by sending the same information from several separate laser transmitters. These are mounted in the same housing, or link head, but separated from one another by distances of about 200 mm. Most likely, at least one of the beams will arrive at the target node with adequate strength to be properly received. This approach is called spatial diversity.
- **Particulate Buildup:** FSO systems are often subject to particulate buildup, mostly due to dust and/or dew. Care needs to be taken to keep the optics clean at all times.
- **Swaying Buildings:** FSO systems deployed on very tall buildings are often subject to sway due to wind or seismic activity. This affects beam aiming. The problem can be dealt with in two ways: through beam divergence and active tracking. With beam divergence, the transmitted beam is allowed to diverge, or spread, so that by the time it arrives at the receiving link head, it forms a fairly large optical cone. This approach has been used by FSO vendors like Lightpointe Communications Inc., San Diego (Ref. 13). A more sophisticated and expensive solution to the problem is to use an active tracking system. This is based on movable mirrors that control the direction in which the beams are launched. A feedback mechanism continuously adjusts the mirrors so that the beams stay on target (Ref. 7).
- **Safety:** The safety of FSO systems is often a cause for concern because lasers are used for transmission. The two major concerns are related to human exposure to laser beams (especially to the eye) and high voltages within the laser systems and their power supplies. Generally, the FSO equipment works at one of two wavelengths: 850 nm or 1550 nm. Lasers at 1550 nm are usually used for transmission, although they are much more expensive than the ones that work at 850 nm. This is because infrared radiation at 1550 nm tends not to reach the retina of the eye, being mostly absorbed by the cornea. Regulations allow these longer wavelength beams to operate at higher power than the 850 nm beams, by about two orders of magnitude. The power increase can boost link lengths by a factor of at least five while maintaining adequate signal strength for proper link operation. Alternatively, it can boost data rates considerably over the same length of link. Therefore, a 1550 nm laser system is a good solution to achieving high data rates at long distances in the presence of poor propagation conditions (like fog) (Ref. 4, 7).

Table 3. SONAbeam 155-M: Maximum Range for Various Weather Conditions (Ref. 12)
(including a 2 dB margin for pointing error)

Worst-Case Weather Condition	Link Margin for 1550 nm (dB/km)	Maximum Range (km)	Excess Power, Clear Day
Clear-air absorption, urban haze and smog, scintillation	<1.5	>6	–
Heavy rain (25 mm/hr)	5	3.2	62x
Extreme downpour (75 mm/hr); moderate snowfall; light fog	13	1.7	257x
Heavy snow; light fog (visibility: 0.5 km)	20	1.25	500x
White-out snowstorm; heavy fog	30	0.92	1000x
Very dense fog (visibility: 1-2 blocks)	60-100	0.35-0.55	2820x–7080x

THE BECHTEL FSO INITIATIVE

Bechtel Telecommunications, Frederick, Maryland, has commissioned an FSO system, which has been operational since March 2002. The FSO equipment being used is fSONA's SONAbeam 155-M (Ref. 11). The 155-M is optimized for high-availability links from 200 to 3,400 meters and supports most standard protocols, including OC-3, STM-1, Fast Ethernet, and FDDI (fiber-distributed data interface).

The availability, as advertised by the manufacturer, can be up to 99.999 percent at appropriate link ranges for given weather conditions. More on the SONAbeam 155-M can be found at Ref. 14.

The FSO link is set up between Bechtel Park Building 2 (BP2) and a Holiday Inn hotel complex approximately 800 meters away. The FSO link is illustrated in **Figure 7** (solid black line). **Figures 8 (a)** and **8 (b)** show a close-up of the fSONA equipment and its placement on the Bechtel building (BP2).

Table 4 summarizes the link budget for the SONAbeam 155-M installed at the Bechtel premises. This link budget provides highly conservative estimates even at perfect propagation conditions with nearly no atmospheric losses.

The excess link margin is obtained after allowing 2 dB margin for pointing variation. Also, any value greater than 0 dB means that the link can be used at the specified range and weather conditions. **Figure 9** illustrates the performance of the system.

On the day of this test, the FSO system was started at 8:49:21 on March 20, 2002, and was terminated slightly more than 24 hours later. It can be seen that the system reached a steady peak of around 310 μW till the time it was shut down. The system was tuned to a data rate of 125 Mbps. Comparing the expected receive signal levels projected in Table 4, one would think that the system has outperformed significantly. This however, may not be true, as the link budget estimates provided within Table 4 are extremely conservative.

Table 4. Typical Link Budget for the SONAbeam 155-M at the Bechtel Premises (Ref. 16)

Attribute	Value
Link range	800 m
Window losses	None
Smog conditions	None
Fog/rain/snow losses	None
Expected receive signal, clear day installation—optimal pointing	76 μW = 0.382 V
Minimum acceptable signal, clear day installation—optimal pointing	57 μW = 0.286 V
Excess link margin in good weather, overcast day	14.6 dB = 29.1 times than required
Excess link margin in good weather, full sun-scintillation, mid-day	13.2 dB = 21.1 times than required
Excess link margin for selected fog/rain/snow condition	15.5 dB = 35.5 times than required
Minimum expected receive power for selected fog/snow/rain condition	52.8 μW = 0.264 V

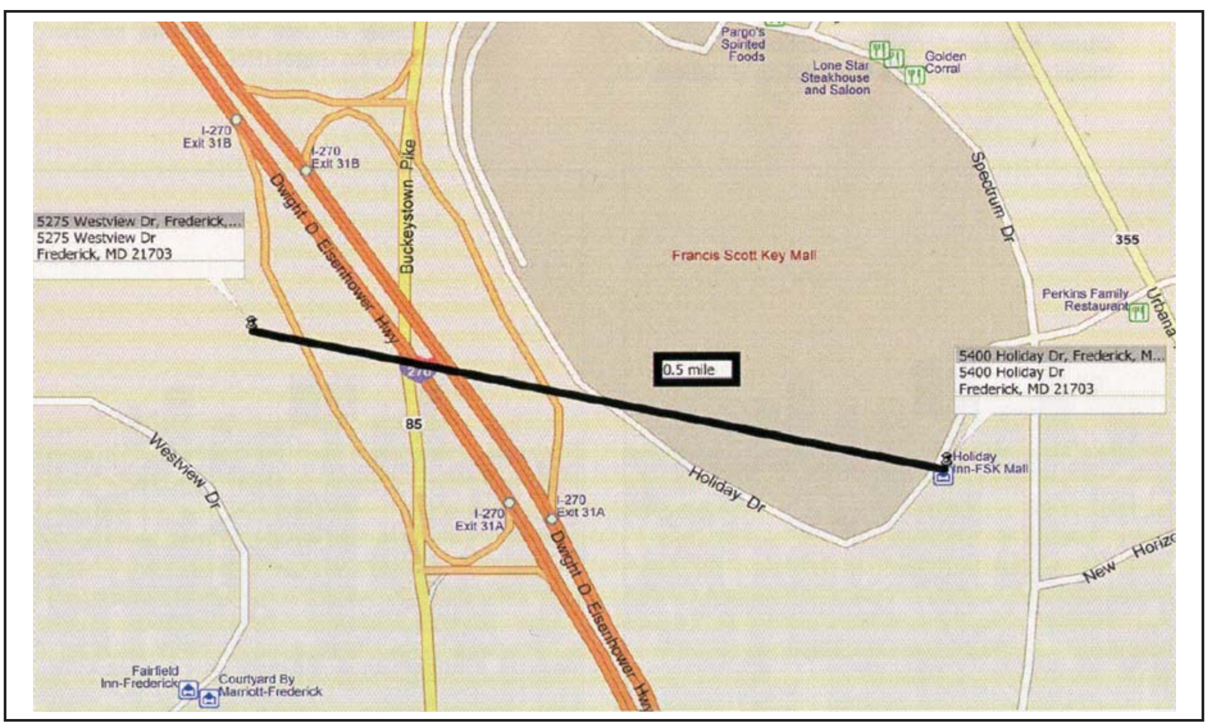

Figure 7. The Bechtel Telecommunications FSO Link

(a)

(b)

Figure 8. fSONA FSO Equipment at Bechtel Park-2 Premises (Ref. 15)

fSONA APPLICATION—BASE STATION HOTELING

According to Ref. 8, FSO systems could be used to link BTS (base transceiver station) hotels to the remote sites. This is illustrated in **Figure 10**. The BTS hotel is linked to the remote sites through FSO links. The remote sites require a transceiver system capable of converting the available spectrum into a digital stream that can be transitioned to the mobile RF links.

The fSONA SONAbeam 1250 and ADC Digivance™ (Ref. 18) can be used to accomplish this. The ADC Digivance converts 25 MHz of RF spectrum into a digital pipe of 1.482 Gb of bandwidth. The SONAbeam 1250 (see **Table 5**) is an FSO transmission system that transports the 1.482 Gb bandwidth pipe. Combined, the system extends the full capability of an existing (and very expensive) BTS to a remote distributed antenna location within 1 mile of the hub BTS location. The key benefits of using the FSO system are speed of deployment and reduced costs in new antenna deployments by 50 percent or more.

The scenario illustrated in Figure 10 is specific to a dense urban location, e.g., beltways. According to Ref. 17, local carriers like Cingular and Verizon estimate the

Table 5. fSONA Products for BTS Hotel Application (Ref. 17)

Product	Range	
	Clear-air (km)	Practical (km)
SONAbeam™ 1250-S	2.25	1
SONAbeam™ 1250-M	3.5	2
SONAbeam™ 1250-AT	8	3

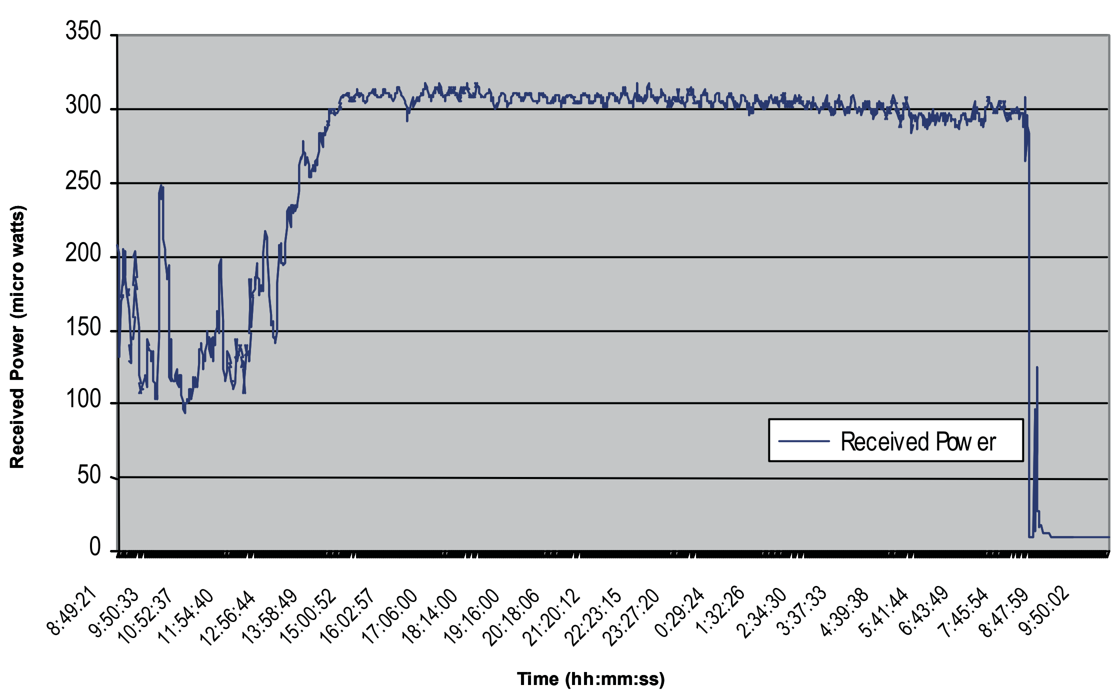

Figure 9. Received Power versus Time Over a 24-hour Period

typical distance between the BTS hotel and the remote sites to be less than 2 km. Initial evaluation of prospective BTS hotel sites on the east coast of the U.S. have revealed that only 10 percent of the sites are within the reach of a fiber backbone (Ref. 17). This would mean the requirement of new fiber build-outs at almost all locations, which is financially unacceptable. An FSO link between the BTS hotel and the remote site could be the solution to fast, easy, cost-efficient deployment of BTS hotel architecture. However, this would be impractical for non-urban locations where the distances between the BTS hotel and the remote sites become a challenge to deploying an FSO system. Currently, fSONA's products listed in Table 5 could meet the criteria for a dense urban BTS hotel deployment.

CONCLUSIONS

Optical wireless is a mature and reliable approach for broadband access. There has been tremendous increase in high-bandwidth applications at the edge of the network. However, this is only possible with high-speed connectivity between the edge and the core of the network. The absence of a last-mile bridge affects not only the end user, but also the service provider who would face delays in laying fiber and building optical infrastructure. Service providers need a means to accelerate the completion of optical networks and allocate high bandwidth at the edge so that they can generate revenue quickly.

FSO systems offer a viable solution toward building optical connectivity in a cost-effective, quick, and reliable manner in certain situations. FSO systems have been engineered to provide performance comparable to other access technologies, offering high capacity and availability (99.999 percent with an RF wireless or DSL [digital subscriber line] back-up), lower cost per Mbps/month when deployed, and rapid deployment in less than an hour. FSO systems can have a wide range of applications ranging from telecommunication backhaul networking to being a viable last-mile alternative, and should be considered when conditions permit.

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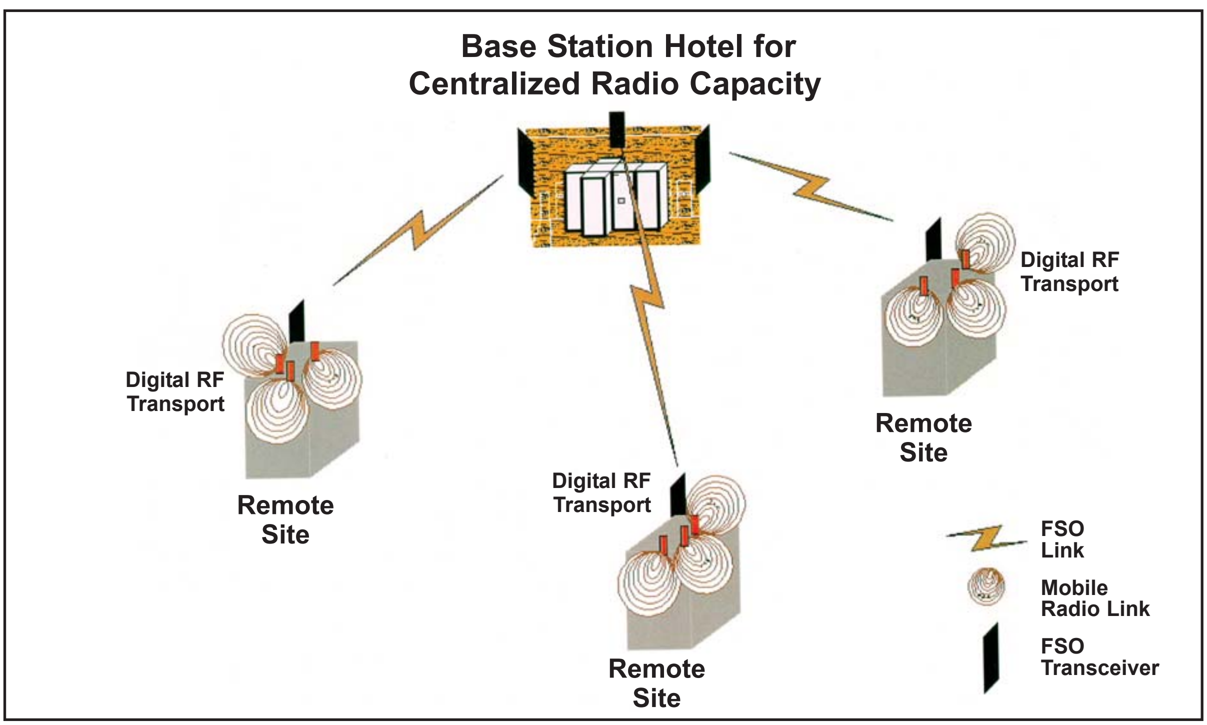

Figure 10. Base Station Hoteling Using FSO (Ref. 8)

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BIOGRAPHY

Nathan Ramasarma

"Nathan" Ramasarma joined Bechtel Telecommunications in October 2002 as staff scientist engineer and has been working on performance analysis of broadband wireless systems at the TDR laboratory in Frederick, Maryland.

Nathan was recently a graduate research assistant with the CWT (Center for Wireless Telecommunications) at Virginia Tech. His research activities were in the field of broadband wireless communications, which led him to write his Master's thesis on interference modeling for NLOS (non-line-of-sight) PMP broadband wireless systems.

Nathan was born in Kerala, India, and received his Bachelor's degree in Electronics and Communications Engineering from the University of Madras.