Flexible Optical Wireless Links and Networks

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ABSTRACT

The worldwide demand for broadband communications is being met in many places by installed single-mode fiber networks. However, there is still a significant "first-mile" problem, which seriously limits the availability of broadband Internet access. Free-space optical wireless communications has emerged as a viable technology for bridging gaps in existing high-data-rate communications networks, and as a temporary backbone for rapidly deployable mobile wireless communication infrastructure. Optical wireless links possess many advantages over RF wireless links, such as massive data rate capacity and freedom from regulation, and offer physical link security because of their fundamentally low probability of intercept or detection. Because free space laser communication links can be easily and rapidly redirected, optical wireless networks can be autonomously reconfigured in a multiple-connected topology to provide improved network performance. In this article we describe research designed to improve the performance of such networks along terrestrial paths. The issues we will address will include effects of atmospheric turbulence, obscuration, and transmitter and receiver design. Using topology control algorithms, we have demonstrated that multiple-connected rapidly reconfigurable optical wireless networks can provide robust performance and high quality of service at high data rates (up to and beyond 1 Gb/s).

INTRODUCTION

Direct line-of-sight optical communications has a long history. Ancient peoples signaled with fires and smoke. The heliograph, which allowed the sun's rays to be reflected from a sender to a receiver, and with a movable mirror allowed the transmission of Morse code, was used by the U.S. Army for communications well into the 20th century. Ships still communicate via flags and signaling lamps. Claude Chappe's semaphore, introduced in 1793, allowed the transmission of messages at rates of about 1 character/s at speeds of over 500 km/h by the use of relay semaphore towers. The use of lasers, and to a lesser extent LEDs, is the latest version of line-of-sight optical communications, and has become known as optical wireless (OW) or free-space optical (FSO) communications. Optical wireless in its current reincarnation is a young technology. Although test systems of this sort were operated in the '60s, the technology did not catch on. Optical fiber communications had not been developed, and a need for a high-bandwidth bridging technology did not exist. The proliferation of high-speed optical fiber networks has now created the need for a high-speed bridging technology that will connect users to the fiber network, since most users do not have their own fiber connection. This has been called the "first" or "last" mile problem.

Optical wireless is not the only solution to the bridging problem, and is presently less developed than relatively low-data-rate radio frequency (RF) wireless used for this purpose. RF wireless is limited in data rate because of the low carrier frequencies involved, and because it is a "broadcast" technology, which is generally regulated and must operate within allocated regions of the spectrum. Spread-spectrum RF, especially emerging ultra-wideband (UWB) technology, can avoid spectrum allocation provided transmit powers are kept very small (to avoid interference problems), but this generally limits the range to a few tens of meters.

THE FIRST-MILE PROBLEM

Fiber optic networks exist worldwide, and the amount of installed fiber will continue to grow. With the implementation of dense wavelength-division multiplexing (DWDM) the information-carrying capability of fiber networks has increased enormously. At least 10 Tb/s of capacity had been demonstrated as of early 2002. This capacity would, in principle, allow the simultaneous allocation of 10 Mb/s each to one million subscribers on a single fiber backbone. The problem is, however, to provide these capacities to actual subscribers, who in general do not have direct fiber access to the network. Currently, the most that is available to most consumers is wired access to the network, since fiber comes to the telephone companies' switching stations in urban

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or suburban areas, but the consumer has to make the connection to this station. Clever utilization of twisted-pair wiring has given some consumers network access at rates from 128 kb/s to 2.3 Mb/s, although most access of this kind through digital subscriber line (DSL) is limited to about 144 kb/s. Cable modems can provide access at rates of about 30 Mb/s, but multiple subscribers must share a cable, and simultaneous usage by more than a few subscribers drastically reduces the data rates available to each. The bridging problem could be solved by laying optical fiber to each subscriber, yet without assurance about the demand for this service from enough subscribers, the various communications service providers are unwilling to commit to the investment involved, which is estimated at $1000/household.

Optical wireless provides an attractive solution to the first-mile problem, especially in densely populated urban areas. Optical wireless service can be provided on a demand basis without extensive prior construction of an expensive infrastructure. Optical transceivers can be installed in the windows or on the rooftops of buildings, and communicate with a local communication node, which provides independent optical feeds to each subscriber. In this way only paying subscribers receive the service. The distance from individual subscribers to their local node should generally be kept below 300 m, and in many cases in cities with many high-rise apartments, this distance will be less than 100 m. These distances are kept small to ensure reliability of the optical connection between subscriber and node.

Deployment of optical wireless network architectures and technologies as extensions to the Internet is contingent on the assurance that their dynamic underlying topologies (i.e., links and switches) are controllable with ensured and flexible access. In addition, this wireless extension must provide compatibility with broadband wireline networks in order to meet requirements for transmission and management of terabytes of data.

The wireless extension of the Internet is going to be dynamic, and characterized by base-station-oriented architectures [1]. Base station architectures may include fixed and mobile nodes (routers and communications hardware and software) and may be satellite-, airborne-, and/or terrestrial-based. The base station topologies (links and switches) can be autonomously reconfigurable and self-healing. Because the base stations (IP routers, switches, high-data-rate optical transmitters and receivers, amplifiers, etc.) include Internet-like technology using emerging commercial communications hardware, they will be cost effective.

Optical Wireless as an Alternative to RF Wireless

The RF spectrum is becoming increasingly crowded, and demand for available bandwidth is growing rapidly. However, at the low carrier frequencies involved, even with new bandwidth allocations in the several gigahertz region, individual subscribers can obtain only modest bandwidths, especially in dense urban areas. Because conventional wireless is a broadcast technology, all subscribers within a cell must share the available bandwidth, cells must be made smaller, and their base station powers must be limited to allow spectrum reuse in adjacent cells. Recent research has shown that RF wireless networks are not scalable, and the size and number of users is limited. Optical wireless provides an attractive way to circumvent such limitations. This line-of-sight communications technology avoids the wasteful use of both the frequency and spatial domains inherent in broadcast technologies. Optical wireless provides a secure high data-rate channel exclusively for exchanging information between two connected parties. There is no spectrum allocation involved since there is no significant interference between different channels, even between those using the exact same carrier frequency.

Optical wireless systems can be made highly directional: there are no undesirable broadcast side lobes as would exist, for example, even with relatively directional microwave point-to-point links. Electromagnetic radiation, whether this be RF radiation or lightwaves, is limited in the directionality it can achieve by the fundamental phenomenon of diffraction. Diffraction is the ability of electromagnetic radiation to leak around the edge of apertures, and to provide energy in regions of space where, in simplistic terms, there should be shadow. The magnitude of diffraction can be quantified by the use of the so-called *diffraction angle*, which for an aperture of a particular size (e.g., a microwave dish or optical telescope used to direct a laser beam) describes the way in which the beam of radiation spreads out. For a transmitter aperture of diameter D, the diffraction angle is

$$_{diff} \sim /D.$$

Consequently, for equivalent sized apertures a microwave signal at 2 GHz has a diffraction angle almost 100,000 times larger than a laser operating at 1.55 m. This has an even more dramatic effect on the footprint of the transmitted signal in a given range, which is a measure of the area of the beam at the receiver location. In the case above the microwave signal has spread into an area that is almost 100 million times larger than that of the highly directional laser beam. This is wasteful of transmitter energy, and the spillover of energy presents a source of interference to other receivers in the area. The energy that is not intercepted by the designated receiver also provides an opportunity for unintended recipients of the signal to exploit its information content. This compromises the security of the transmitted data, which, even if it is encrypted, allows a third party to be aware of the existence of the communications channel.

An optical wireless communications link suffers from none of the drawbacks described above. The high carrier frequency, which for a 1.55 m laser is almost 200 THz, provides almost 100,000 times more information carrying capacity than a 2 GHz microwave signal. For reliable operation over a 1 km range an optical wireless system can easily have a footprint diameter at

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the receiver of only 50 mm, although for practical reasons involving pointing and tracking this might be adjusted to be 1 or 2 m. The spillover, or scattering, of light at the receiver location is virtually immune to interception by a third party, which provides not only a high degree of physical security for the link, but also immunity from traffic analysis.

There are a number of additional advantages of OW systems for the unobtrusive configuration of communication networks, especially within densely populated urban areas, not least of which is avoiding additional installed fiber optic infrastructure. The current cost of building an installed fiber optic infrastructure within a city in North America can be up to $1 million/mi. An OW network does not require large, possibly unsightly, antenna towers. There is no likelihood of some of the public paranoia that has accompanied the sighting of cellular base stations in urban and suburban areas.

Frequently Asked Questions

People often ask whether atmospheric conditions such as fog, rain, and snow make line-of-sight optical communications problematic and unreliable. The answer is no, *provided the length of links between nodes is not too long*. Typical OW links use transmitter powers in the range from 0d Bm (1 mW) to 20 dBm (100 mW). Optical receivers can be fabricated with sensitivity of –35 dBm for operation at synchronous optical network (SONET) rates. With a 2 mrad beam divergence over a 1 km range, the geometric loss for a receiver with a diameter of 200 mm is 23 dB. With a 50 mm receiver at a range of 200 m the geometric loss is 21 dB. For a 100 mW transmitter the corresponding link margins are 26 dB and 34 dB, respectively. Allowing a 10 dB safety margin, these links could handle obscuration of 16 dB/km (light fog) and 120 dB/km (dense fog), respectively. These simple calculations show that short-range links have a clear advantage for penetrating very dense fog. It has been estimated that in North America over ranges up to 300 m optical wireless links provide 99.99 percent availability over a single connection. This represents much less than one hour of nonavailability per year. RF wireless cannot provide such reliability because of bandwidth and interference problems. Our research has demonstrated that we can provide 1 Gb/s communication rates over 1 km ranges even through very dense (50 dB/km) fog by the use of special transmitter and receiver designs.

What about birds and other objects passing through the beam? In a packet-switched network such short-duration interruptions are handled easily by packet retransmission.

Optical Wireless System Eye Safety

The safety of OW communications systems can be assessed using the American National Standards Institute (ANSI) Z136.1 Safety Standard.[1] The maximum intensity that can enter the eye on a continuous basis depends on the wavelength, whether the laser is a *small* or *extended* source, and the beam divergence angle.

The lasers used in OW systems generally emit beams with a Gaussian intensity profile. For a Gaussian beam at the transmitter with spot size[2] w and total power P, the maximum intensity at the center of the beam is

$$I_0 = 2P/ \ w^2.$$

For example, an OW transmitter with a power of 6 mW and with a spot size of 5 mm has a maximum beam intensity of 153 W/m^2, and a maximum power into the eye of 5.9 mW *even if the beam is viewed right at the transmitter*. Such a transmitter would be eye-safe at 1.3 m and 1.55 m, but not at 78 nm. An OW transmitter with a power of 100 mW at 1.55 m with a spotsize of 10 mm corresponds to a maximum beam intensity of 637 W/m^2, and a maximum power that could reach the eye of 25 mW. This transmitter would provide safe operation even for viewing right at the transmitter with the dark-adapted eye. In general, OW systems operating at 1.3 m are 28 times more eye-safe, and systems operating at 1.55 m are 70 times more eye-safe, in terms of maximum permitted exposure, than OW systems operating below 1 m.

The Effects of Atmospheric Turbulence on OW Links

The atmosphere is not an ideal optical communication channel. The power collected by a receiver of a given diameter fluctuates, but these *scintillations*, which can increase bit errors in a digital communication link, can be significantly reduced by *aperture averaging* [2]. The largest level of scintillation occurs for a small diameter receiver (this is why stars viewed with the naked eye "twinkle"). Clearly, if a large enough receiver were used, and all of a transmitted laser beam were collected and directed to a photodetector, there would be no scintillations. In practice, OW link design requires the selection of a reasonable receiver diameter, which reduces scintillation significantly, yet provides sufficient power collection. Selecting an optimal receiver diameter is quite involved. It requires calculation of various correlation functions of the wavefronts arriving at the receiver as a function of the link length, laser wavelength, and strength of the turbulence.

An additional difficulty is that the receiver must collect light and focus this onto a small area photodetector. This is especially true for high-data-rate links. The fluctuating wavefronts at the receiver front aperture are focused to spots that "dance" around in the focal plane. Consequently, either the focal spot dancing must be smaller than the size of the photodetector, or the receiver must be defocused and the photodetector overfilled to avoid signal fades. This phenomenon does not cause significant problems for links < 200 m. An on-off-keyed (OOK) digital scheme, which amounts essentially to a "photons in the bucket" approach to the detection of a 1, offers the best approach to dealing with the inherent fluctuations of atmospheric turbulence.

[1] Available from the Laser Institute of America,13501 Ingenuity Drive, Suite 128, Orlando, FL 32826. Phone: (407) 380-1553, fax: (407) 380-5588, (800) 34-LASER. lia@laserinstitute.org

[2] 1/e2 radius of the beam intensity profile

Such a scheme can also be enhanced if necessary by adding additional coding to the channel to further reduce the probability of error. For longer ranges, in principle, turbulence effects can be mitigated with an adaptive optic transmitter/receiver, but this is far from routine.

We have shown that the bit error rate (BER) of a long (> 1 km) OW link can be quite high because of scintillation and spot-dancing-induced signal fades, but can be significantly reduced by the use of a *delayed diversity* scheme [3, 4]. In a delayed diversity scheme, a data stream is transmitted twice, in either two separate wavelengths or two polarizations with a delay between the transmissions that is longer than correlation times in the atmosphere. These correlation times are generally on the order of 10 ms. The delay between transmissions 1 and 2 is reintroduced at the receiver, but in the opposite channel to the one that was delayed on transmission. Then the two channels are reinterleaved with an OR gate and the digital signal detected. Simplistically, the BER is reduced because if a given bit is detected in error because of a fade in the received signal at that time, there is an independent opportunity to redetect this bit at a later time that is longer than the memory time of the channel. The improvement that can be produced by this technique is shown in Fig. 1. This figure shows the performance of a 1 km long OW link operating at 1.3 m at 1 Gb/s for various levels of scintillation at the receiver.

The receiver decision threshold is set halfway between the average signal levels corresponding to the arrival of a 1 and a 0.

Although WDM approaches to this diversity scheme are satisfactory, orthogonal polarization channels offer a simple solution. Because the atmosphere is not intrinsically chiral, left- and right-circularly polarized waves should be identically affected by turbulence, so no significant perturbation of the polarization state of a lightwave that has propagated through turbulence is expected. Indeed, the transmitted signal itself could be polarization-shift-keyed (PolSK). This approach has not received much attention in fiber optic communications systems because of their depolarizing properties.

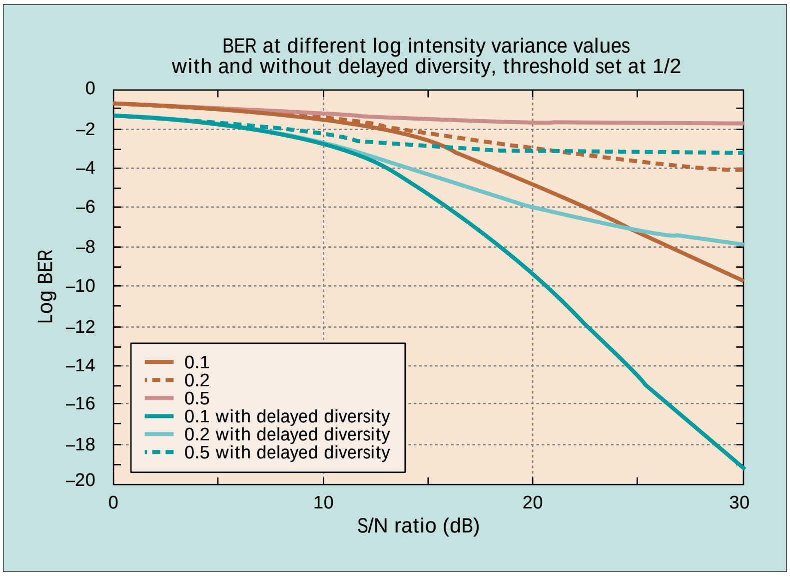

Figure 1. *Variation in BER for a 1 km link operating at 1.3 mm at 1 Gb/s with and without the use of time-delayed diversity.*

Free-Space Optical Wireless Links with Topology Control

While there is an emerging technology and commercial thrust for switching between OW and RF point-to-point links [5], there is no topology control in this Internet-like context. Our experiments with reconfigurable OW networks suggest that significant improvements in data rate as well as autonomous reconfigurability of wireless extensions to the Internet are possible.

Topology control in OW and RF wireless networks involves the dynamic selection and reconfiguration of physical networks. In OW networks, obscuration of links by fog and snow can cause performance degradation manifested by increased BER and transmission delays. In a biconnected network (implemented with transceiver pairs), changes in the link state need to be mitigated. In our optical wireless network approach, responses to link state changes include:

- Varying the transmitter divergence, power, and/or capacity
- Varying the transmission rate of the link
- In link failure, redirection of laser beams, which can be steered to direct their energy toward another accessible RX/TX node

This reconfiguration may be designed to meet multiple objectives such as biconnectivity, maximizing received power, and minimizing congestion and BER. Algorithms and heuristics are used for making efficient decisions about the choice of network topology to achieve a required level of performance and provide necessary physical reconfigurability [6].

Our research aims to answer fundamental questions regarding:

- How OW networks can be changed or autonomously reconfigured
- How such change is determined

This requires the ability to control the network topology in a proactive way. Our approach to autonomous topology control and beam reconfiguration is as follows:

- The topology discovery and monitoring process
- The decision making process by which a topology change is to be made
- The dynamic and autonomous redirection of beams to new receiver nodes in the network
- The dynamic control of these beams for either penetration of obscuration (OW) or adaptive allocation of RF smart antennas to redistribute power and link quality.

Topology Discovery and Monitoring

Our approach to OW networking and communi-

The topology, which is the set of links and switches, must be continuously monitored using an optical "probe." This monitoring and discovery of potential neighbors can be achieved by determining the link "cost" or characteristic level.

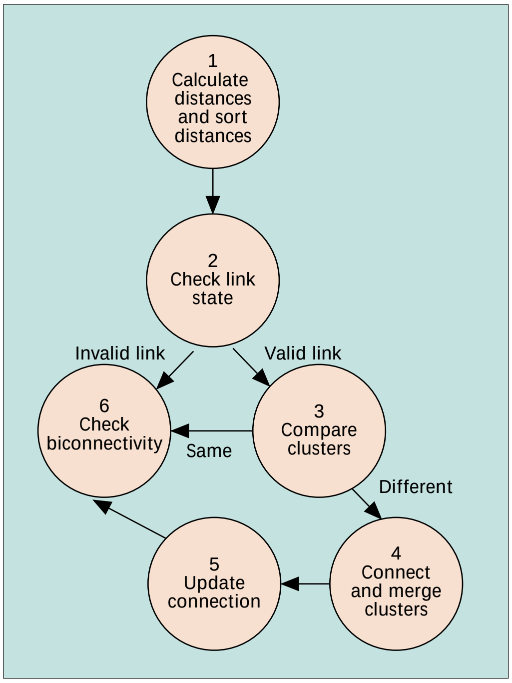

Figure 2. *Topology reconfiguration.*

cations is based on gigabit-per-second communications using optical links over ranges less than 2 km, and optical probes and communications protocols used to assess the state of the network, and ultimately provide optimized performance.

We are investigating high-data-rate free-space optical links that can be reconfigured dynamically. Their key characteristics include:

- Optimal obscuration penetration
- Dynamic link acquisition, initiation, and tracking
- Topology control to provide robust quality of service

The topology, which is the set of links and switches, must be continuously monitored using an optical probe. This monitoring and discovery of potential neighbors can be achieved by determining the link cost or characteristic level (e.g., received power, BER, fade, obscuration). We use received power to monitor the state of each link.

Topology Change and the Decision Making Process

Each node or switch in a biconnected network includes two transceivers. Each receiver/transmitter pair can exchange link state information, such as received power and current beam divergence.

The received power provides an indirect measure of the likely BER. A protocol is needed that allows the nodes to exchange neighboring BER values and enables them to make optimizing decisions about the overall network, such as keeping BER $< 10^{-9}$.

The adjustment or reconfiguration decisions at an OW node are made as follows:

- *Can changing the beam divergence, bandwidth/capacity, or transmitter power compensate for the increased value of BER on the link?*
- *If not, how should the network topology be reconfigured?*

The first corresponds to changing the variables at each node in the network; changing the bandwidth capacity of the link changes the cost (i.e., average end-to-end delay).

The second requires a threshold for the overall end-to-end delay such that the new topology is reconfigured when the optimal end-to-end delay exceeds the threshold. The next question is which algorithm to apply to find the optimal topology out of $(N - 1)!/2$ possible topologies. It must be kept in mind that the algorithm must be executed in real time, as the speed of optical networks is typically several hundred megabits per second or more. We have developed low-complexity (computational and communication) algorithms and heuristics that involve the execution of heuristic algorithms to choose the best possible topology by evaluating the topologies and configuring or selecting topologies based on such characteristics as transmit powers, link fades, and signal to noise ratio.

Topology Reconfiguration: A Free-Space Optical Example

We have developed a prototype OW system, which included a small-scale reconfigurable fixed OW system using four biconnected PCs, 155 Mb/s transceivers, steerable galvo-mirrors, and TCP/IP sockets with topology control algorithms programmed in C++. The topology configuration for the network is based on some particular constraints (i.e., distance between nodes in this case). The topology information is in the form of the position matrix and link state matrix of each node. In this case, the objective requires biconnectivity, in the sense that the network can achieve full-duplex capability in topology.

In this algorithm, each node makes decisions based on its local information. All executed steps are shown in Fig. 2 and explained in the following paragraphs.

Calculate and Sort Distances: Distance is defined as the time for the host to redirect the beam to reach a particular neighbor, and is calculated from the information in a position matrix. Once the calculation is finished, the results are sorted in nondecreasing order and stored in a distance table, and the corresponding node pairs are stored in a node connectivity table.

Check Link State: The objective is to determine the link status for node pairs, which are listed in the node connectivity table. The link state is determined by sending a ping to every neighbor in the node table.

Compare Clusters: In order to connect all the nodes and form the network topology, we use a clustering method. Clustering is defined as a method for successively connecting or grouping a set of nodes that are linked with each other. Every cluster has one incoming link and one outgoing link. Initially, each node will form its own cluster (i.e., the number of clusters is equal to the number of nodes). Node *i* will look up neighboring node *j*, and try to determine if they are in the same cluster or not. To determine whether two nodes belong to the same cluster, they will exchange and compare the information about their cluster. If this information is the same, then they belong to the same cluster. If not, step 4 is executed. Finally, a network will be established if and only if there is only one cluster left and every node is inside that cluster. The algorithm terminates if the number of clusters is equal to one.

Connect and Merge Clusters: If nodes are not members of the same cluster, they attempt to make a connection (the optimal one with respect to the constraint). Each cluster has two links that can be used as either an incoming or outgoing link (refer to step 2). Thus, from these two clusters we will have four possible connections. The algorithm will select the minimum distance among these four and pick that as the connection. The two unused links (one from each previous cluster) become the incoming and outgoing links from the new cluster. All the nodes inside the merged clusters should be aware of this change and update their cluster information.

Update Connection: Once a new connection occurs, the host is updated.

Check Biconnectivity: This process is executed by checking the connection matrix (i.e., the network graph). Since the biconnectivity information has been generated for every node in the network, the network has been autonomously reorganized. If there is no valid link status, this state is directly executed. It implies that either this node or a set of nodes is isolated.

Our prototype algorithms for topology control required 8.7 ms for distribution of information and topology reconfiguration. Of this time, 1.6 ms was required for actual redirection of the laser beam. The BER during the topology configuration process is shown in Fig. 3. The data indicate that BER increases as a function of data rate, up to approximately 10^{-6}, averaged over 2500 topology rearrangements within a 24 h period.

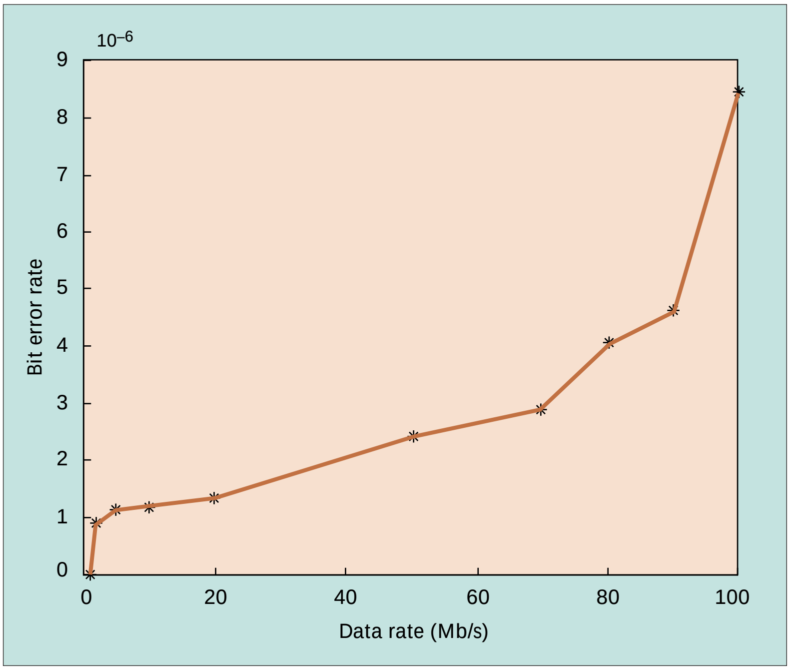

Figure 3. *BER due to the topology control process.*

Dynamic Redirection of Laser Beams

When a laser beam must be redirected to a new node, it may be necessary to discover the location of the new node. In one network design, nodes broadcast their location with RF wireless signals at lower data rates than are used by the OW connections. Information about node location could involve the use of Global Positioning System (GPS) information broadcast from each node. In other situations nodes must discover each other with limited or no information about where other nodes are located. Under good atmospheric visibility conditions this can be done with the aid of passive or active retroreflectors placed at each node, which will provide a return signal to a transmitter that is being scanned and is looking to establish a link.

Link or beam redirection can take place in a number of ways, for example:

- By redirecting a laser beam from one node to a different node
- By activating a new laser at a node that has lost biconnectedness, which points to a different node than the laser whose link has failed

The redirection of a laser could involve a movable mirror, either a galvo-type mirror, a microelectromechanical system (MEMS) mirror, a piezoelectric scanner, an acousto-optic beam deflector, or an electro-optic beam deflector. Alternatively, a laser array (e.g., a VCSEL array) can provide redirection of the output beam if the VCSEL array is placed in the focal plane of the TX. Each element of the array can be activated independently and provide beam redirection of the output from the TX. This is different from redirection of the beam in a directed RF antenna system, in which phasing of antenna elements provides RF antenna lobe steering.

Summary

We present an overview of the issues affecting the implementation of an optical wireless networking scheme, including atmospheric effects, eye safety, and networks with autonomous topology control and laser beam configuration that includes:

- The topology discovery and monitoring process
- The decision making process by which a topology change is made
- The dynamic and autonomous redirection of laser beams to new receiver nodes in the network

A prototype of this approach has been implemented as a proof of concept.

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