Multi-Gigabits-per-second Optical Wireless Communications

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Abstract

Optical wireless is increasingly becoming an attractive option for multi-gigabit-per-second (multi-Gb/s) short range (up to 2 km) links where laying optical fiber is too expensive or impractical. For such links, a tracking scheme is essential to maintain proper pointing of the transceivers at each other to establish error-free communication. For the transmitter, the tracking ensures that a narrow beam is pointed at the receiver with minimal residual jitter in the presence of atmospheric beam-wander, building sway, and wind/temperature loading effects. For the receiver, the tracking ensures a tight focus on a relatively small detector (typically less than 100 μm) in the presence of atmospheric induced angle-of-arrival fluctuations, roof vibration caused by air-conditioning units, and wind loading effects. We present data on some of these angular noise sources as well as noise suppression capabilities of our tracking subsystem. Active tracking in our systems allows us to use sub-milliradian beams for communication. Error-free one-kilometer links at 1.25 Gb/s have been established with less than 1 mW of optical transmitter power.

I. Introduction

Optical Wireless communication, also known as free-space optical (FSO), has emerged as a commercially viable alternative to RF and millimeterwave wireless for reliable and rapid deployment of data and voice networks. RF and millimeterwave technologies allow rapid deployment of wireless networks with data rates from tens of Mb/s (point-to-multipoint) up to several hundred Mb/s (point-to-point). However, spectrum licensing issues and interference at unlicensed ISM bands will limit their market penetration. Though emerging license-free bands appear promising, they still have certain bandwidth and range limitations. Optical wireless can augment RF and millimeterwave links with very high (>1 Gb/s) bandwidth. In fact, it is widely believed that optical wireless is best suited for multi-Gb/s communication.

The biggest advantage of optical wireless communication is that an extremely narrow beam can be used. As a result, space loss could be virtually eliminated (<10 dB). But few vendors take advantage of this and use a wide beam to ensure enough signal is received on the detector even as the transceivers' pointing drift. This scheme is acceptable for low data rates, but becomes increasingly challenging at multi-Gb/s rates. Our approach has been to shift the burden from the communication system to a tracking system that keeps the pointing jitter/drift to less than 100 μrad. With such small residual jitter, sub-milliradian transmitted beam widths can be used. In so doing, the data communication part of the system is relatively simple and allows us to scale up to, and even beyond, 10 Gb/s.

The main challenge for optical wireless is atmospheric attenuation. Attenuation as high as 300 dB/km in very heavy fog is occasionally observed in some locations around the world [1]. It is impossible to imagine a communication system that would tolerate hundreds of dB attenuation. Thus, either link distance and/or link availability has to be compromised. It is also obvious, that the more link margin could be allotted to the atmospheric attenuation, the better the compromise is. As a result, in the presence of severe atmospheric attenuation, an optical link with narrow beam and tracking has an advantage over a link without tracking.

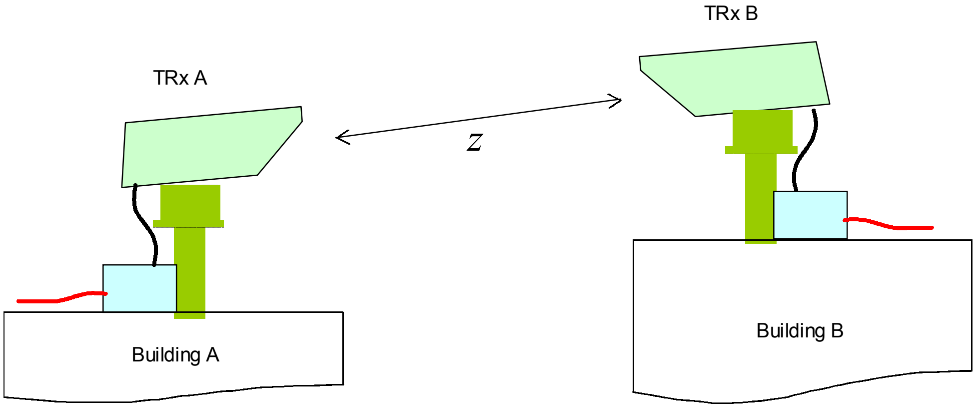

Figure 1: Schematic showing optical wireless transceivers mounted on top of two buildings.

II. Optical Wireless Link Budget

An optical wireless link typically consists of two transceivers, A & B, separated by some distance, z (Figure 1). Each transceiver (TRx), in turn, is made up of one or more lasers (transmitter) and a photodetector (receiver). Optics (telescopes, lenses & mirrors) shape the transmitted laser beam and focus the received signal on the photodetector. The link is designed such that enough signal from lasers on one transceiver reaches the photodetector on the other transceiver to distinguish ones and zeroes with negligible error. Consider a link with transmitted optical power from all the lasers, P_T, and the receiver sensitivity, S_R. Unless otherwise noted, all powers are given as average power. The received power, P_R, is given by:

$$P_R = (\eta_T \cdot \eta_S \cdot \eta_R)\ P_T$$

where η_T and η_R are losses in the transmitter optics and receiver optics, respectively; and η_S is the fraction of transmitted power collected by the receiver. The quantity P_R / S_R is the link margin. Let us examine how each part of the communication system impacts the link budget.

Transmitter

For cost reasons, many FSO vendors traditionally have used the 780 nm to 850 nm near-infra-red spectrum. For numerous reasons, we believe the 1550 nm band, the choice of the fiber-optic telecommunication industry, is better suited for optical wireless. The main benefit of the band is ability to transmit more power. Because of the properties of the human eye, the safe or allowable power density at 1550 nm is nearly 50 times that at 780 nm. Consequently, a significantly more power can be transmitted in the 1550 nm band to overcome attenuation by fog. The Food and Drug Administration (FDA) considers power density of about 100 mW/cm^2 at 1550 nm (or 1 mW/cm^2 at 780 nm) safe to the unaided eye [2]. Assuming a beam with a Gaussian profile is transmitted with 25 mm 1/e^2 diameter, approximately 245 mW at 1550 nm can be transmitted and still be eye-safe. Other benefits of 1550 nm band include reduced Solar background and scattering (attenuation) in light haze/fog, as well as a wide range of available components because of the heavy investment in the 1550 nm technology for the telecom sector. The disadvantages of the band are slightly lower detector sensitivity (by a few dB), higher price of components and more difficult alignment. However, all of these are outweighed by considerably higher available transmitter power.

A typical high speed 1550 nm laser has a slope efficiency of 0.03-0.2 W/A. Consequently, one needs to design a laser driver that can swing several hundred milliamp of current to reach the eye-safe power limits. In our current example, more than an amp of current would be needed to reach the maximum allowed power. While this is achievable for bandwidths of few hundred MHz, it is a rather difficult design for multi-GHz bandwidth. At present, commercial laser driver chips are capable of only about 100 mA modulation current at 2.5 Gb/s. Moreover, no currently available high speed 1550 nm laser could produce

Data rate	Sensitivity		Detector size
	PD	APD	
155 Mb/s	-36 dBm	-43 dBm	300 μm
1.25 Gb/s	-26 dBm	-33 dBm	75 μm
2.5 Gb/s	-23 dBm	-29 dBm	50 μm
10 Gb/s	-14 dBm	?	30 μm

Table 1: Sensitivities and diameters of commercial detectors for different data rates at 1550 nm. These are not theoretically achievable numbers but just a sample of what is readily available.

a quarter of a Watt of power so multiple transmitters would have to be used. The drawback of this approach is that transmitters would have to be synchronized at higher data rates. Though expensive, a better option is erbium-doped fiber amplifier (EDFA). EDFAs offer a viable option of amplifying modulated low power optical signal and transmitting significant optical power with greater than 1 GHz modulation.

Receiver sensitivity

For detection of multi-Gb/s signal, the increased noise bandwidth fundamentally limits the receiver sensitivity. Commercially available photodiode (PD) and transimpedance amplifier (TIA) combinations can achieve -26 dBm at 1.25 Gb/s (see Table 1). InGaAs avalanche photodiodes (APD) can improve the sensitivity by up to 10 dB, but often at the cost of a smaller detector size and reduction in saturation power. Forward error correction (FEC) can also improve sensitivity by about 4 dB or more, but at the price of significant complexity. At the multi-Gb/s rates, decoding of higher gain convolutional or turbo codes become difficult and only the simpler Reed-Solomon codes are practical.

Perhaps the most significant challenge of moving up to multi-Gb/s is the problem associated with the detector size. Because of the capacitance, higher bandwidth detectors are inherently smaller in size. Commercial photodetectors range in size from 30 μm for 10 Gb/s to 70 μm for 2.5 Gb/s. The limited field-of-view (FOV) of these small detectors require the pointing to be particularly accurate as discussed later.

Optics losses

Optical losses through the transmitter optics (η_T) and receiver optics (η_R) attenuate the signal. Good optical engineering practices, such as minimizing optical surfaces and using anti-reflection coatings, can often minimize transmitter and receiver losses. To reduce background noise, narrow bandpass filters are typically used. These are often the largest loss elements. Depending on the complexity of the optical train, losses can vary between 2 to 5 dB.

Space loss

The dominant loss in a wireless link (η_S) is the result of capturing only a small portion of the transmitted signal at the receiver. In the RF world, this is essentially the product of the transmitter gain, space loss and receiver gain. Alternatively, the parameter η_S is proportional to the square of the ratio of the receiver aperture to the transmitted beam diameter at the receiver. FSO vendors typically use 6-8 mrad beam divergence for their low data rate products. Higher data rates are usually accomplished by reducing beam divergence to 2 mrad. Though this may be a convenient way to establish a link, what should dictate the beam divergence is the environment (i.e. pointing jitter & drift). For example, 8 mrad (< 0.5 degrees) beam divergence at 1km, results in an 8 m beam diameter. Therefore, a 150 mm receiver collects less than 0.04% of the transmitted signal – equivalent to a loss of –35 dB. Decreasing the beam divergence to 2 mrad reduces the loss to -23 dB.

Effect of the atmosphere

As mentioned earlier, it is desirable to have as much excess margin as possible to mitigate atmospheric effects, such as fog. On a sunny day, the atmosphere is clear and the margin is useful to overcome fades caused by turbulence. On a foggy day, the margin is used to overcome signal attenuation. The dominant

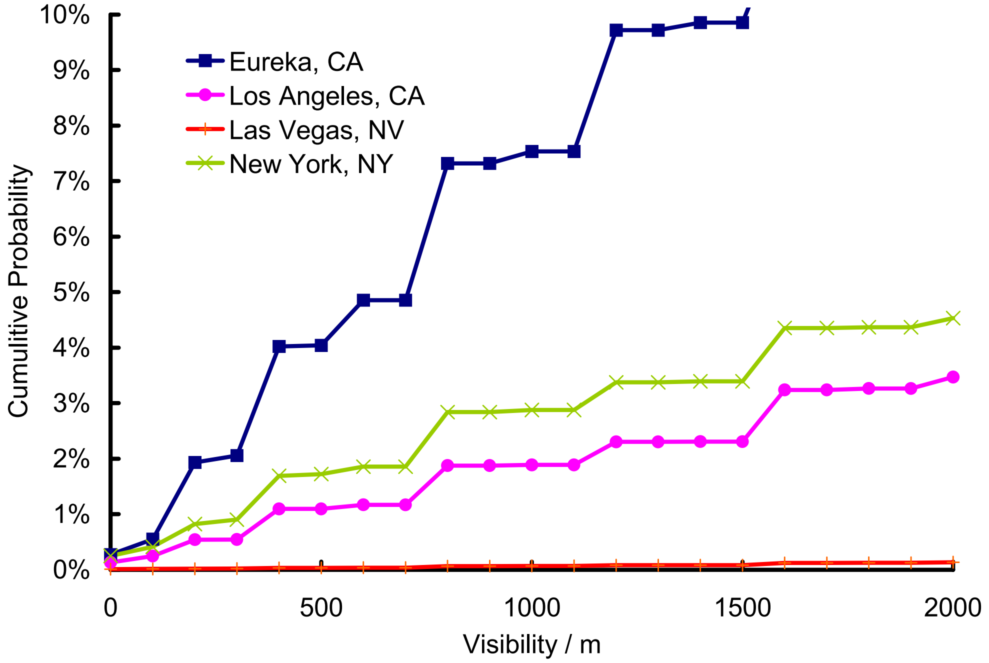

Figure 2: Visibility statistics for four North-American cities collected at local airports between 1982 and 1997 [3].

atmospheric effect that impacts optical communication is attenuation of the signal by scatter and absorption. Molecular scatter & absorption of major atmospheric constituents is relatively insignificant. Though rain & snow can cause attenuation up to approximately 40 dB/km and 100 dB/km, respectively, fog by far is the largest problem. In extremely heavy fog, attenuation as high as 300 dB/km has been reported [1]. Figure 2 shows the cumulative probability distribution function of visibility at a few North American cities [3]. Clearly, either link distance or link availability has to be compromised, as part of the network design.

In the absence of attenuating elements, the atmosphere is best modeled as a random phase medium that changes with time. To a first order, the atmosphere introduces a random beam deflection. For example, on a sunny day the rising hot air makes the index of refraction of air go up with height and in extreme conditions can result in a mirage. Such an index of refraction change near the transmitter tends to deflect the beam causing “beam wander”. The same effect near the receiver, however, causes the beam to appear to have come from a different place (angle-of-arrival fluctuations). The magnitudes of these effects are largely dependent on the index of refraction fluctuations and propagation distance. In extreme conditions over distances of several kilometers, the atmospheric induced tilt can vary by be as much as 100 μrad at a rate of tens of Hertz.

Second order effects, i.e. small-scale turbulence, can also play a big role in disrupting optical communications. Small-scale phase fluctuations introduced at the source can result in scintillation (speckle pattern) after several hundred meters of propagation. Depending on the speckle size and receiver aperture, the dynamic atmosphere causes fades in the received signal. Phase perturbations near the receiver will make the focused spot size on the detector much larger than the diffraction limit. When the detector size is only few tens of microns, this spot size increase further reduces minimal allowable transceiver mispointing. Thus, high bandwidth tracking is made necessary by a turbulent atmosphere for high data rate links.

	Without tracking	With tracking
Transmitter power	30 dBm	30 dBm
Transmitter losses	3 dB	3 dB
Transmitter mispointing allowance	6 dB	3 dB
Space loss	30 dB	14 dB
Receiver losses	3 dB	3 dB
Receiver mispointing allowance	6 dB	3 dB
Receiver sensitivity	-23 dBm	-23 dBm
Foul weather signal attenuation allowance (margin)	**5 dB**	**27 dB**

Table 2: Example of a 2.5 Gb/s, 2 km link budget with and without tracking

Link budget analysis example

Suppose a 2 km link is desired at 2.5 Gb/s. Furthermore, the system has to be eye safe. Using four 1550 nm transmitters from the earlier example, up to about 1 W average power could be transmitted, while still being eye safe. Receiver sensitivity for 2.5 Gb/s is -23 dBm (see Table 1). Further assuming a 150-mm receiver aperture and beam divergence of 2 mrad FWHM for the non-tracking case (a commonly used divergence for gigabit non-tracking systems) and 0.3 mrad FWHM for the tracking case (a six fold improvement in pointing accuracy). Based on these assumptions available margin for signal attenuation due to weather events such as fog, rain and snow is estimated in Table 2. The foul weather allowance in the table is transmitted power minus receiver sensitivity (in dBm) and minus all the losses. As is seen from the example, tracking allows a significantly larger margin for atmospheric attenuation and fades.

III. Pointing

Pointing is important both at the transmitter and the receiver. The transmitter has to be pointed accurately to ensure efficient delivery of energy to the receiver. The receiver has to be pointed properly to ensure that the signal entering the receiver aperture makes it to the detector. To ensure good reception, the divergence of the transmitted beam and the receiver field-of-view has to be greater than the beam (or pointing) jitter.

Let us assume that a transmitter with a full-width-at-half-maximum (FWHM) beam divergence of θ is used. A 3 dB mispointing allowance implies that the transmitted beam should never point more than $\pm\theta/2$ from the nominal direction. Let us further assume that the long-term statistics of mispointing takes on a Gaussian distribution having a standard deviation σ. If we want the pointing loss to be less than 3 dB 99.999% of the time, then the FWHM must be greater than 8σ. Clearly, the optimum beam divergence is dictated by the pointing jitter and greatly depends on the location and mounting of the transceiver. Some vendors have reduced the beam divergence for their high-bit-rate products down to 2 mrad. We believe that this is unacceptable as it requires the long-term pointing standard deviation to be less than 0.25 mrad.

The field-of-view (FOV) of the receiver is equal to the ratio of the detector size to the focal length:

$$FOV = \frac{d}{f} = \frac{d}{D} F\#$$

where f is the effective focal length, D is the receiver aperture and d is the detector diameter. The quantity F# is the f-number, or ratio of focal-length to diameter, of the system. Assuming an aggressive F# = 1 and D = 150 mm telescope, the field of view of the receiver is a mere 0.5 mrad for a 75 μm detector. The FOV

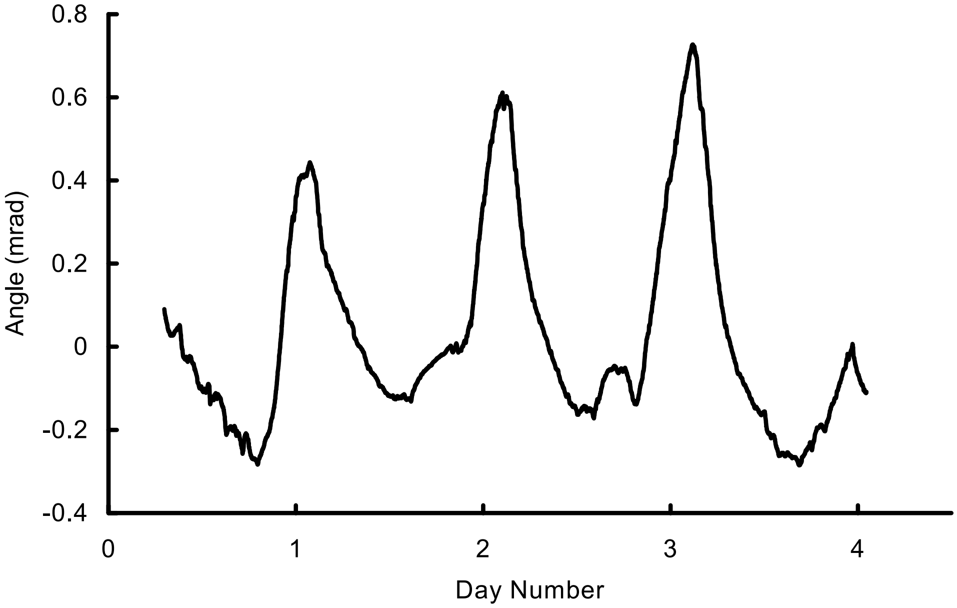

Figure 3: Time-averaged plot of pointing drift over four days clearly showing the diurnal changes. The day numbers mark noon.

can be improved, but not by much, with custom photodetector packages and unconventional telescope design. To achieve the high availability desired by the Telecom Industry, the standard deviation of the receiver pointing jitter has to be well below 100 μrad which is impractical without active tracking.

Even in the absence of the atmosphere, keeping two transceivers pointed accurately at each other at all times to better than one milliradian is a challenge. A great deal depends on how and where the transceivers are located. When a transceiver is mounted on a roof of a high building, building sway contributes significantly to the pointing error. A high-rise building can sway more than a meter (equivalent to one milliradian for a one-kilometer link). The roof itself often houses air-conditioning and ventilation units, as well as lift and other mechanisms that cause vibration in the low tens of Hertz. Moreover, some roofs are not very solid and can deform when someone walks on them. Temperature changes (diurnal and seasonal) and uneven heating by the sun can deform the mount enough to throw the pointing off. Some FSO customers have indicated that they need to realign the transceiver units few times a year for this very reason. Optical wireless transceivers and their mounts have enough wind resistance that they are tilted in heavy winds. To make things worse, building owners, for liability reasons, do not easily grant approval for putting in penetrating mounts. Non-penetrating mounts on rooftops exhibit even larger pointing fluctuations.

The plot in Figure 3 shows a sample of pointing error observed over four winter days in Southern California. The data was taken on a six-story high building with the transceiver fixed to a solid mount permanently attached to the roof. The second transceiver was placed approximately one kilometer away on a three-story building. It should be noted that the data is scaled from the control signal applied to the actuator and not the sensor output itself. Immediately apparent from the plot is the sharp change in pointing (peaking early afternoon), even in winter days. With nearly a milliradian of drift in just four days, one can expect much greater drifts in the hot summer days. Based on these initial measurements, we believe that optical wireless communication systems need to handle maximum drift and jitter of about 5 mrad. Under some extreme conditions, the transceivers may have to tolerate drifts in the order of a degree.

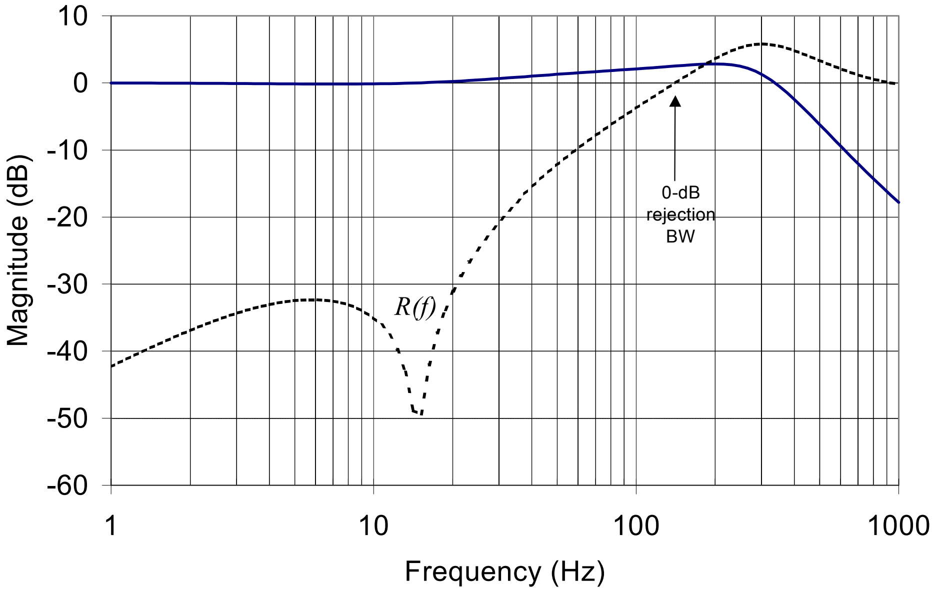

Figure 4: Performance of Optical Crossing's tracking system. The solid line shows the plant output over input response while the dashed line shows the error over input response.

The only way to have low space loss as well as large pointing tolerance is to have an active alignment or tracking mechanism. The tracking system effectively reduces the pointing jitter and allows the use of very narrow transmitted beams and small detectors. We, furthermore, believe that the tracking system should have bandwidth in excess of 50 Hz to correct for most atmospheric effects and mount vibrations. The higher bandwidth tracking is especially critical as one moves to 10 Gbps systems (30 um detectors) or all-optical wireless schemes where light has to be focused on to 9 μm core single-mode fibers (SMF).

IV. Tracking System

Our proprietary tracking system consists of an angle sensor and an actuator with several hundred Hertz bandwidth. As can be seen from Figure 4, the 3-dB closed loop bandwidth is over 400 Hz. A more useful measure of the tracking performance is the disturbance rejection, $R(f)$, (dashed line in Figure 4) which indicates how much of the disturbance is suppressed by the tracking loop. For our system, the zero-dB disturbance rejection bandwidth is approximately 140 Hz. In fact, if one knows the power spectral density (PSD) of the pointing drift/jitter, $N(f)$, and the disturbance rejection of the control system, the residual jitter can be estimated from [4]:

$$\Theta_{\mathrm{rms}}^2 = \int \left| R(f) \right|^2 N(f) \cdot df$$

As discussed earlier, the transmitter beamwidth and receiver field-of-view must be sufficiently greater than Θ_{rms} to have a reliable link. Since $N(f)$ varies from installation to installation, so does Θ_{rms}. Consequently, optical wireless transceivers must be designed for worst-case conditions to minimize customization of the units.

V. Bit Error Rate Results

With the tracking system in place and working, the communication link is quite simple. The data in Figure 5 was collected on an approximately one-kilometer long link with sub-milliradian beam divergence and about 0.1 mW of power transmitted. The systems were initially aligned and the tracking was turned off at about 14:00. With the tracking system turned off, alignment completely degrades in a couple of hours and the bit error rate (BER) increases quickly to statistical maximum of 50% by around 17:00 (see Figure 5). With the tracking turned back on, the error-free connection is immediately recovered.

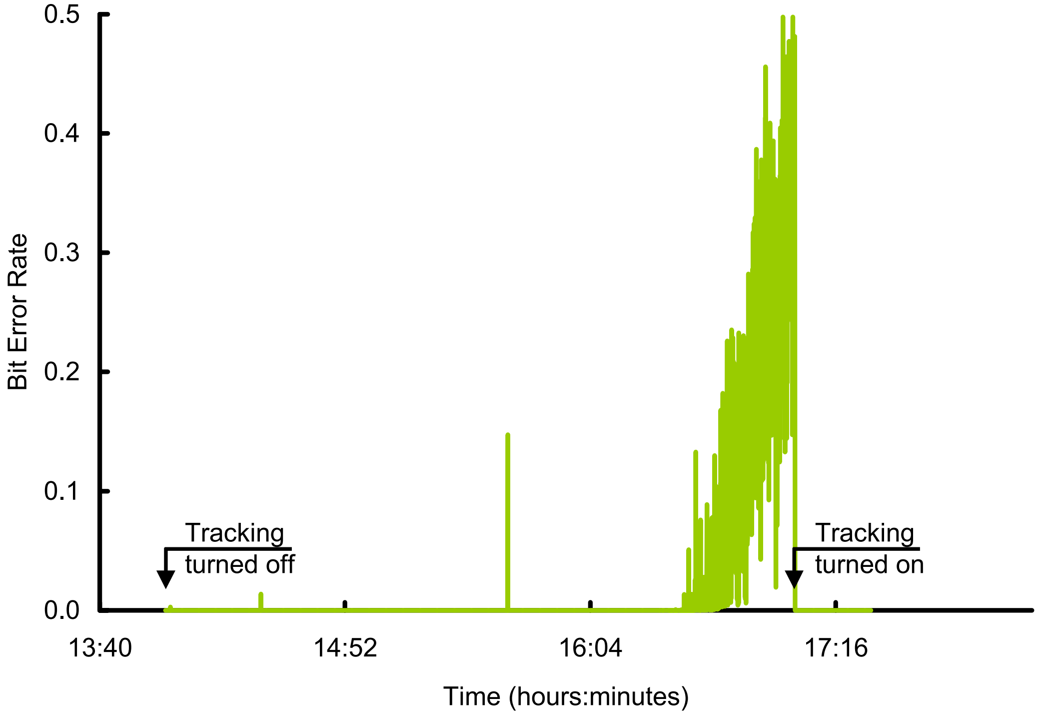

Figure 5: Bit error rate versus time. Data rate of 1.25 Gb/s, distance approximately one kilometer and 0.1 mW average transmitted power.

VI. Conclusions

The greatest challenge in moving from hundred Mb/s to Gb/s optical wireless systems is the small detector size and poor receiver sensitivity at the higher speeds. A high bandwidth tracking system reduces the jitter by correcting pointing errors from various sources. The reduced pointing jitter, therefore, allows the use of narrower transmitted beams and small field-of-view detectors. Narrower beams provide increased link margin that is beneficial in overcoming larger atmospheric attenuation. Furthermore, a tracking system that can tolerate large angular drifts eliminates the need to periodically realign the transceivers, and thus significantly reduces maintenance costs.

We have clearly demonstrated the viability of multi-Gb/s optical wireless links and expect commercial availability of such systems in the near future. As we perfect these gigabit Ethernet and OC-48 products, work has already begun on 10 Gb/s Ethernet and OC-192 optical wireless systems.

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VII. References

1. P.L. Eardley and D.R Wiseley, IEE Proc.-Optoelectron., **143**, 330 (1996)
2. Class 1M limit under International Electrotechnical Commission (IEC) 60825 which has been temporarily adopted by FDA’s Center for Devices and Radiological Health (CDRH)
3. “International Surface Weather Observations 1982-1997”, National Oceanic and Atmospheric Administration
4. S. Lee, et. al., “Pointing and tracking subsystem design for optical communications link between the International Space Station and ground,” SPIE Proceedings Vol. 3932, pp (2000).