OPTICAL WIRELESS: LOW-COST, BROADBAND, OPTICAL ACCESS

by

David A. Rockwell
Director, Advanced Technology
fSONA Communications Corporation
drockwell@fsona.com

G. Stephen Mecherle
Chief Technology Officer
fSONA Communications Corporation
smecherle@fsona.com

INTRODUCTION

The global telecommunications network has seen massive expansion over the last few years, catalyzed by the telecommunications deregulation of 1996. First came the tremendous growth of the long-haul, wide-area network (WAN), followed by a more recent emphasis on metropolitan area networks (MANs). Meanwhile, local area networks (LANs) and gigabit ethernet ports are being deployed with a comparable growth rate. In order for this tremendous capacity to be exploited, and for the users to be able to utilize the broad array of new services becoming available, network designers must provide a flexible and cost-effective means for the users to access the telecommunications network. Presently, however, most local loop connections are limited to 1.5 Mbps (a T1 line). As a consequence, there is a strong need for a high-bandwidth bridge (the "last mile" or "first mile") between the LANs and the MANs or WANs.

Optical wireless systems represent one of the most promising approaches for addressing the emerging broadband access market and its "last mile" bottleneck. These robust systems, which establish communication links by transmitting laser beams directly through the atmosphere, have matured to the point that mass-produced models are now available. Optical wireless systems offer many features, principal among them being low start-up and operational costs, rapid deployment, and high fiber-like bandwidths. Available systems offer capacities in the range of 100 Mbps to 2.5 Gbps, and demonstration systems report data rates as high as 160 Gbps.

This article first considers the attributes of an ideal broadband access system, and then discusses how optical access systems score very high on this list of attributes. Next we quantify the costs associated with these systems, and show that optical wireless offers a significantly lower cost per bit-per-second than that of all established access approaches. Engineering maturity is examined next, and we find that optical wireless systems have developed to the point that carrier-class applications are possible. We close with a brief summary of recent field-test results, which prove that excellent "real-world" performance can be achieved with a properly designed system.

BROADBAND ACCESS: IDEAL ATTRIBUTES

In order to establish a metric for assessing the attractiveness of optical wireless, this section reviews the ideal attributes of a generic broadband access approach. One of the most significant attributes is cost, which includes the following elements:

- low installation cost as well as cost per bit/second associated with each subscriber,
- low first-in cost (i.e. the cost of launching access service for the first few subscribers)

The ideal broadband access approach should also offer rapid deployment, so carriers can begin generating revenue as quickly as possible. Another important attribute is the capability to provide a high capacity to each subscriber, thereby enabling multiple services to be utilized. Moreover, this capacity should be easily scalable, not only in overall bandwidth, but also in the total number of subscribers that can use the access equipment. The ideal access approach should be available a high percentage of the time (up to 99.999% availability), and able to propagate data over relatively long distances.

Each broadband-access approach offers a "zone of advantage," that is, each approach offers a more-optimal performance for certain specific applications and deployment strategies. However, no single approach provides all of the attributes listed above. For example, although dedicated fibers offer massive capacity, they are expensive, and carriers miss many months of potential subscriber revenues while waiting for fibers to be deployed. Fiber-based passive optical networks (PONs) represent a highly attractive approach, due to the relatively low cost per subscriber. However, the inherent high capacity of fibers is shared among a number of users, thereby reducing the capacity per user, and the deployment times can still be quite long, depending on the location of any particular subscriber. Radio frequency (RF) fixed wireless systems are a credible access option, but they are limited in data rate, require FCC licensing, are subject to rain fading, and are costly relative to other access schemes.

The logical consequence of this situation is that one must select an approach that best meets the needs of a specific deployment. Optical wireless represents an approach with wide and broadly based applications appeal because of its many features. Optical wireless complements both RF and wireline networks, providing fiber-like capacity at data rates up to 1 Gbps and more with a cost per bps that is among the lowest available, at ~ $ 4 / Mbps / month. Given that no spectrum license is required, the start-up costs are significantly lower than for RF wireless. Optical wireless systems can be rapidly deployed; once a suitable line of sight is identified, a point-to-point link can typically be installed and brought to operational status in approximately one hour or less. Well engineered optical wireless links, which properly account for the statistical occurrence of fog, can achieve an availability of 99.9 %, or even full carrier-class availability of 99.999 % if one installs a (lower capacity) RF link or DSL back-up. Finally, optical wireless systems are "network-friendly" in that they can be:

- engineered to be protocol-independent,
- implemented in cellular or mesh architectures as well as point-to-point links,
- sent from roof-top to roof-top or through office windows,
- designed to be compatible with common monitoring protocols to ensure the highest level of successful implementation, and
- redeployed to a different subscriber location if desired, for example, if an existing subscriber no longer requires an optical wireless connection due to receiving a direct fiber-optic connection.

Given these attributes, it is clear then why optical wireless systems are being implemented in a broad range of applications and markets, including local exchange carriers, ISPs, network service integrators, and businesses ranging in size from small ISPs to major carriers and ILECs. Market-analysis studies predict healthy growth of optical wireless systems, with annual growth rates in the range of 80 to 90 % and projected total global sales of more than $ 2 B in 2005.

COST

Because cost is such an important factor in the broadband access market segment, a cost comparison of optical wireless and a number of established broadband access technologies is summarized in Table 1. The final figure of merit defined for this comparison is (cost / Mbps / month), and optical wireless, at $ 4 / Mbps / month, is half as expensive as the next-lowest-cost alternative. The most expensive technologies cost more than 80 times as much as optical wireless. This cost advantage arises from the combination of high, fiber-like data rates and a low implementation cost. These cost advantages are so compelling that the individual numbers in Table 1 can vary somewhat without affecting the conclusion that optical wireless is the lowest-cost access approach. An even more compelling case for optical wireless cost-effectiveness applies for higher data rates of 622 Mbps and up.

ENGINEERING MATURITY

The engineering maturity of optical wireless is often underestimated, due to a misunderstanding of how long such systems have been under development. Historically, optical wireless was first

Table 1. Cost comparison among established broadband access technologies and optical wireless. The monthly costs for the RF and optical systems correspond to full depreciation of the equipment costs over three years.

Access Medium	Speed (Mbps)	Equipment Cost ($)	Cost per Mbps ($)	Monthly Cost ($)	Cost/Mbps/Mo ($)
Dial-Up	0.056	--	--	20	357
Satellite (DBS)	0.4	--	--	50	125
Cable Modem	1.5	--	--	50	33
DSL (min)	0.144	--	--	49	340
DSL (max)	8	--	--	1200	150
T-1	1.54	--	--	300	195
T-3	45	--	--	3000	67
RF					
Median price, 6 vendors	155	45,000	290	1250	8
Optical Wireless					
SONAbeam 155[a]	155	20,000	130	555	4

[a] This product operates at 155 Mbps at distances up to 2 km, depending on fog conditions.

demonstrated by Alexander Graham Bell in the late nineteenth century (prior to his demonstration of the telephone!). Nevertheless, essentially all of the engineering of these systems was done over the past 40 years or so, mostly for defense applications. By addressing the principal engineering challenges, this aerospace/defense activity established a strong foundation upon which today's commercial optical wireless systems are based.

First, such systems can be designed to be eye-safe, which means that they pose no danger to people who might happen to encounter the communications beam. Laser eye safety is classified by the

International Electrotechnical Commission (IEC), which is the international standards body for all fields of electrotechnology. While the IEC is an advisory agency, its guidelines are adopted by the regulatory agencies in most of the world's countries. A laser transmitter that is completely safe when viewed by the unaided eye is designated IEC Class 1M. In the U.S., laser eye safety is controlled by the Center for Devices and Radiological Health (CDRH), a division of the Food and Drug Administration (FDA). Currently, the CDRH is in the process of adopting the safety classifications of the IEC.

Note, however, that the eyesafe limits vary with wavelength. The optical wireless hardware currently on the market can be classified into two broad categories – systems that operate at a wavelength near 800 nm and those that operate near 1550 nm. Laser beams at 800 nm are near-infrared and therefore invisible, yet like visible wavelengths, the light passes through the cornea and lens and is focused onto a tiny spot on the retina. This is schematically illustrated in Figure 1 (a), which applies for visible and near-infrared wavelengths in the range of 400 to 1400 nm. The collimated light beam entering the eye in this retinal-hazard wavelength region is concentrated by a factor of 100,000 times when it strikes the retina. Because the retina has no pain sensors, and the invisible light does not induce a blink reflex, at 800 nm the retina could be permanently damaged by some commercially available optical-wireless products before the victim is aware that hazardous illumination has occurred. In contrast, Figure 1 (b) schematically shows that laser beams at wavelengths greater than 1400 nm are absorbed by the cornea and lens, and do not focus onto the retina. Because of these biophysical properties of the eye, wavelengths > 1400 nm are allowed approximately 50 times greater intensities than wavelengths near 800 nm. This fact can be exploited by specifying a wavelength in the 1550 nm range, where the factor of fifty additional laser power allows the system to propagate over longer distances and/or support higher data rates.

Second, as is well known from common experience, fog substantially attenuates visible radiation, and it has a similar affect on the near-infrared wavelengths that are employed in optical wireless systems. Note that the effect of fog on optical wireless radiation is entirely analogous to the attenuation – and fades – suffered by RF wireless systems due to rainfall. Similar to the case of rain attenuation with RF wireless, fog attenuation is not a "show-stopper" for optical wireless, because the optical link can be engineered such that, for a large fraction of the time, an acceptable power will be received even in the presence of heavy fog. This important element of link engineering begins with the collection of fog-statistics data, which show what percentage of the time the fog attenuation will be greater than a certain value. Then, the fog statistics for the subscriber's location are used to determine how much fog attenuation (in dB/km) must be accommodated to guarantee a given value of availability (e.g. 99.9 %). Next, the link design calculations are consulted to determine how much link margin is allocated to fog attenuation. Finally, the maximum link length is calculated according to the simple equation

$$\text{Length (km)} = \frac{\text{Link Margin (dB)}}{\text{Fog Attenuation (dB/km)}}$$

When this simple analysis is applied to actual deployments, locations having frequent and heavy fog will have shorter allowable links for a given availability. Alternatively, a relatively fog-free site might be able to accommodate link lengths of several km using identical optical wireless equipment.

Optical wireless-based communication systems can be enhanced to yield even greater availabilities. In particular, by including a RF wireless link or DSL as a back-up, one can offer availabilities of 99.999%.

Another example where practical engineering yields a reliable, low-cost optical wireless approach is the ability to maintain sufficiently accurate pointing stability without invoking the cost, complexity, and reliability issues associated with the use of an active pointing-stabilization approach. This preferred low-cost, fixed-pointed approach is schematically shown in Figure 2, where we see that the transmitted beam is broadened significantly beyond its near-perfect minimum beam divergence angle, and the receiver field of view is broadened to a comparable extent. The broadening of the transmitted and received fields of view leads to large pointing/alignment tolerances and a very low probability of building motion being of sufficient magnitude to take the link down. Well engineered hardware exploits this approach of designing for loose alignment tolerances; therefore, it is possible to perform initial alignment of the transceivers at opposite ends of the link during installation and then leave them unattended for many years of reliable service. Note that this approach is facilitated for systems operating at wavelengths >1400 nm, because the higher allowable eyesafe powers at such wavelengths allow the transmitted beam to be significantly broadened spatially while still maintaining an adequate intensity at the receiver.

Other features of optical wireless systems that have accrued from the long engineering history include:

- systems have been designed to allow simple, rapid installations, in an hour or less, assuming a suitable line of sight has already been identified;
- scalability to multiple types of architectures, protocols, and higher data throughputs.

FIELD-TEST RESULTS

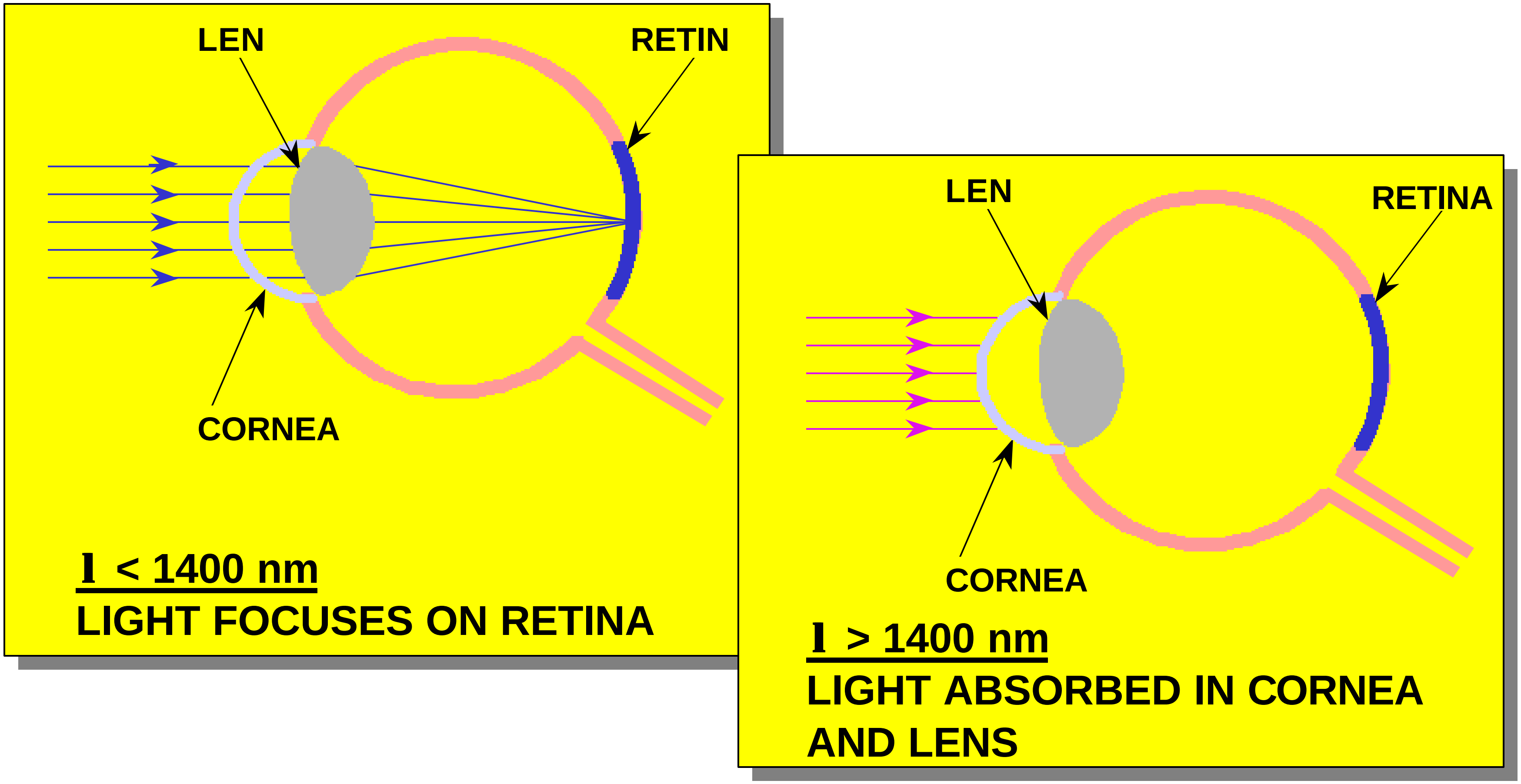
The final proof of the viability of any broadband access approach, including optical wireless, is the successful conclusion of rigorous field-tests. In this context it is appropriate to summarize some recent results that were achieved for a 750 meter link near Vancouver, B.C., Canada; this link was operated

24 hours per day, 7 days per week, for a total of 30 days (or 43,200 minutes) late last year. Weather conditions varied widely during the tests, and included periods of steady drizzle, heavy driving rain, and multiple occasions of moderate fog. The only time the link dropped out was a 20 minute period when fog reduced the visibility to ~ 50 meters. These results, then, demonstrate a total link availability of 99.95 % through *all* weather conditions.

The best results were recorded during October, 2000, when not a single bit or packet error was observed over measurement periods of 24 hours, for a total of 11 terabits and a BER of $<10^{-13}$. More-typical results were a BER of 10^{-9} to 10^{-12} with occasional power transients of typically ~ 0.1 to 5 msec, and 5 such events in 24 hours.

CONCLUSION

Optical wireless represents a mature, reliable approach for broadband access. Such systems have been engineered to provide robust performance that is highly competitive with other access approaches, offering high capacity, excellent availability of 99.9 % (99.999 % with an RF wireless or DSL back-up), lowest cost per bps, and rapid deployment in ~ 1 hour. These systems are compatible with a wide range of applications and markets, and they are sufficiently flexible as to be easily implemented using a variety of different architectures. Because of these features, market projections indicate healthy growth for optical wireless sales. This market potential will be met with well engineered systems, designed for high-volume manufacturing, that are available immediately.



(a) (b)

Figure 1. Laser eye safety standards vary with wavelength, due to the fact that shorter wavelengths from 400 to 1400 nm are transmitted through the cornea and lens of the eye to be focused into a high-intensity spot on the retina, while wavelengths > 1400 nm are absorbed in the cornea and lens prior to being focused. This difference allows much greater incident intensities for wavelengths > 1400 nm without risking eye damage.

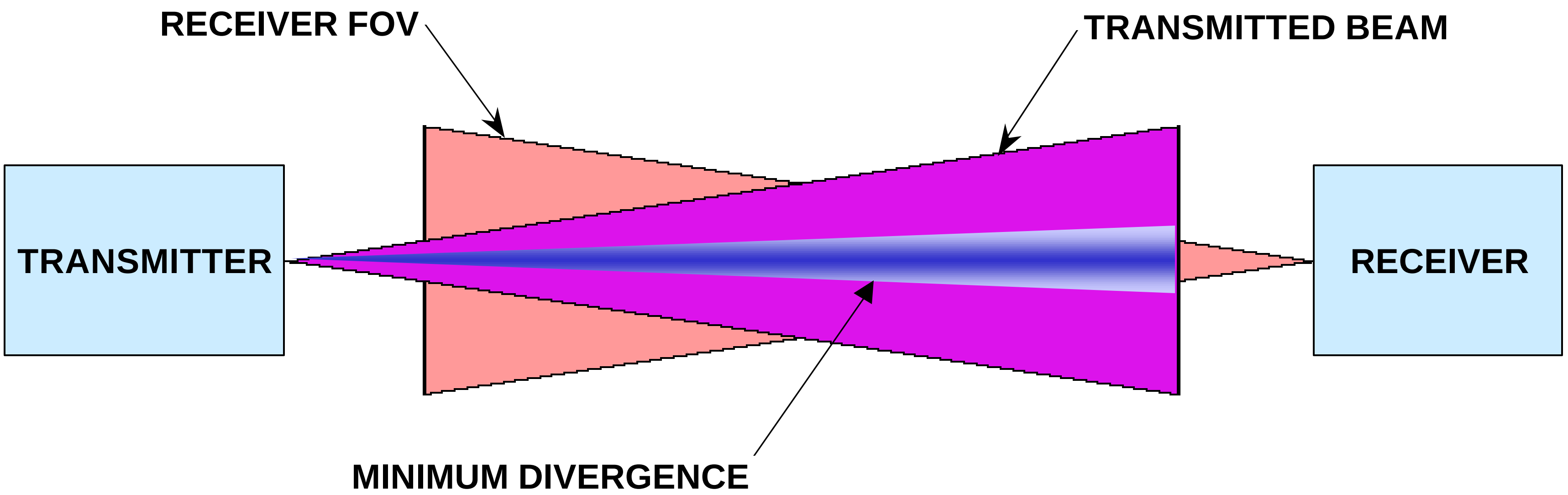


Figure 2. Schematic diagram of a fixed-pointed optical-wireless system showing how the pointing / alignment tolerance can be increased by broadening the transmitted beam significantly beyond its near-perfect minimum beam divergence angle, and broadening the receiver field of view to a comparable extent.