# fSONA Communications Corporation

Free Space Optical Networking Architecture
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*Wireless at the speed of light ….*

# WAVELENGTH SELECTION FOR OPTICAL WIRELESS COMMUNICATIONS SYSTEMS

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fSONA Networks Corp.
100-13200 Delf Place
Richmond BC V6V 2A2
Canada
(604) 273 - 6333

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## 1. INTRODUCTION

We are all aware of the massive expansion of the global telecommunications network. 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. At the present time, however, most local loop connections are limited to 1.5 Mbps (a T1 line). As a consequence, there is presently a strong need for a high-bandwidth bridge (the “last mile”) between the LANs and the MANs or WANs. A number of optical access technologies are now being developed, with the objective being to address the needs of this important emerging optical-access market segment.

One of the most promising of the new access technologies is optical wireless, whereby robust optical transceivers transmit laser beams directly through the atmosphere to form point-to-point communications links. Optical wireless systems offer many features, principal among them being the following:

- low start-up and operation costs, mostly due to the fact that optical wireless is not regulated by the Federal Communications Commission (FCC), and does not require expensive licensing of the needed spectrum;
- high fiber-like bandwidths, with prototype demonstrations from several suppliers achieving capacities in the range of 100 Mbps to 1 Gbps, and laboratory demonstrations reported as high as 40 Gbps

Taken together, these two features indicate that optical wireless offers the lowest cost per bit of any access technology.

Optical wireless systems are not without challenges, however. First, we believe that such systems must be eye-safe, which means that they must pose no danger to people who might happen to encounter the communications beam. This requirement manifests itself in the form of legally mandated upper limits to the intensity of the transmitted laser beam. 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.) These two challenges highlight one of the critical design trades that must be resolved to field a successful optical wireless system: the system must transmit sufficient power that the free-space communication link will be available a high percentage of the time, even with some degree of fog attenuation, but the power must not be so high as to exceed eye-safe limits. Additional trade issues exist as well, and the overall performance of any optical wireless system critically depends on the successful execution of those design trades.

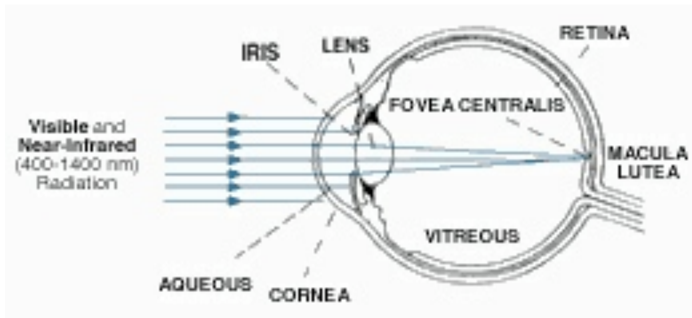
This paper explores one of the most important trade issues, the selection of the optical wavelength. Historically, most developers of such systems have employed wavelengths in the near-visible infrared spectral region (~ 780 nm to ~ 850 nm), principally because of the availability of efficient and reliable direct semiconductor diode-based sources at those wavelengths, and, for the 780 nm devices, the cost advantages of utilizing the same wavelength as is used in CD recorders. While cost is obviously an important factor in the wavelength trade, one must also consider several additional constraints, most notably the need not to exceed eye-safe limits on transmitted intensities under conditions of high data-rate transmissions through heavy atmospheric attenuation (due to fog, for example). Other important trade criteria include overall performance, and the potential for system growth and scalability. When all of these factors are considered, it becomes clear that a more judicious approach is to employ wavelengths near 1550 nm, the same wavelength range used in commercial fiber-optic communications networks.

The following sections review the issues involved in specifying the operating wavelength and support the selection of the 1550 nm wavelength range. We begin by summarizing the issues relating to eye safety, then we consider some of the ways in which the wavelength specification affects the overall performance of the optical wireless system. This is followed by a discussion of several system-level benefits of 1550 nm operation that accrue from being able to leverage the massive investments in 1550 nm technology and the resulting vast technological infrastructure.

## 2. EYE SAFETY

With the proliferation of optical wireless communication products directing laser beams into potentially populated areas, the issue of laser eye safety becomes of increasing significance for public safety and system operator liability. Because biophysical characteristics of the eye are quite different for the two predominant optical-wireless wavelength bands, eye-safety considerations play a key role in the overall system wavelength trades.

1 (a)




1 (b)

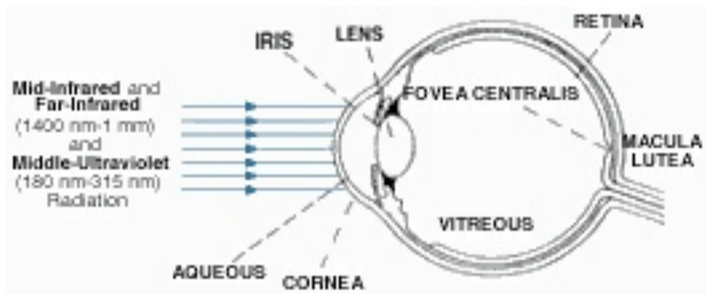



Figure 1. Light absorption and transmission characteristics of the human eye: (a) for visible and near-infrared wavelengths, light is focused onto a small spot on the retina; (b) for mid-infrared, far-infrared, and middle-ultraviolet wavelengths, light is absorbed by the cornea and lens (from Sliney & Wolbarsht, *Safety with Lasers and Other Optical Sources*, Plenum Press, 1980).

The optical wireless hardware currently on the market can be classified into two broad categories – systems that operate near 800 nm wavelength and those that operate near 1550 nm. Laser beams at 800 nm wavelength 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 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) shows that laser beams at 1550 nm wavelength are absorbed by the cornea and lens, and do not focus onto the retina.

It is possible to design eye-safe laser transmitters at both the 800 nm and 1550 nm wavelengths, but due to the aforementioned biophysics the allowable safe laser power is about fifty times higher at 1550 nm. This factor of fifty is important to the communication system designer, because the additional laser power allows the system to propagate over longer distances and/or through heavier attenuation, and to support higher data rates.

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 which is safe when viewed by the eye is designated IEC Class 1M. A transmitter which is also safe when viewed with a 25 mm binocular is designated IEC Class 1. Laser Safety classifications are summarized in IEC Document 60825-1 Amendment 2.

In the United States, laser eye safety is regulated by the Center for Devices and Radiologic Health (CDRH), a division of the Food and Drug Administration. Currently, the CDRH is operating in an interim period while in the process of adopting the safety classifications of IEC 60825-1am.2. Unfortunately, during this interim period some manufacturers are forced to label their products as Class 3B, even though the products are eyesafe according to IEC Class 1M. It may take until 2003 for the CDRH to complete their standards revision, and CDRH is expected to issue guidelines to manufacturers in early 2001 about how to minimize the impact to products during this interim period.

## 3. PERFORMANCE

We begin this section by stating the obvious fact that the ultimate measure of the value of any communications system is whether it can cost-effectively transmit broadband data across a link with an acceptable bit error rate (BER), typically taken as $10^{-9}$ or better. We have seen in the preceding section that the biophysics of the eye leads to an allowable power level at 1550 nm that is approximately 50 times greater than at 780 nm. This higher allowable power is a significant advantage of the 1550 nm wavelength, but a number of other performance-related factors should also be considered in this wavelength trade.

The most significant challenge facing free-space optical wireless systems is posed by atmospheric attenuation, particularly fog. Hence, it is appropriate to ask whether this challenge strongly favors one or the other wavelength ranges. Some optical attenuation processes that occur in the atmosphere are strongly wavelength dependent, such as Rayleigh scattering from air molecules. The attenuation from this scattering process is much greater for shorter wavelengths;

it varies inversely as the fourth power of the wavelength. (Note that the wavelength dependence of Rayleigh scattering has a profound impact on our environment: it is the reason why the sky is blue during the daytime and sunsets are red!) However, Rayleigh scattering and other similar processes are not the most significant loss mechanisms that confront free-space optical wireless. The greatest loss mechanism is Mie scattering from fog. The wavelength dependence of Mie scattering is highly sensitive to the specific nature of the fog droplets, since it is a resonant scattering process that is strongest when the fog droplet size is nearly the same size as the wavelength of the light. In haze and light fog, Mie scattering generally results in reduced attenuation at longer wavelengths. However, attenuation measurements taken under conditions of very low visibility show that this long-wavelength advantage does not always apply. Hence, when designing an optical wireless communications link with an availability target of 99 % to 99.9 %, it is not clear that 1550 nm wavelengths consistently offer an advantage for the low-visibility fog that actually drives the link design.

Nevertheless, the fact that 1550 nm-based system are legally allowed to transmit ~ 50 times more power does favor the longer wavelength. All other factors being equal, the higher power of the 1550 nm systems will translate into superior penetration of fog as well as any other loss mechanism that is nominally the same for the two wavelength bands.

There is one property of the propagation of light that might, at first glance, appear to provide an inherent advantage for the shorter wavelength, namely diffraction. According to the laws of diffraction, for the same medium and the same emitting aperture, the beam spreading due to diffraction is linearly proportional to the transmitted wavelength. This principle signifies that, in the absence of other beam-spreading effects, and assuming all other factors are equal, an 780 nm beam can produce an intensity at the downstream end of the link that is ~ 6 dB greater than for a 1550 nm beam. However, this advantage will essentially never be realized in practical optical wireless systems, since the transmitted beam is almost always spread out well beyond the diffraction limit. This beam spreading is applied to relax the pointing tolerance with which the optical wireless transceivers at opposite ends of the communications link must be pointed.

So far we have just considered the transmission side of the optical wireless link. We must also consider wavelength trades on the receiver side, in particular the receiver photodiode. It is generally true that high-quality photodiodes at both 780 nm and 1550 nm achieve comparable quantum efficiencies. Since a certain minimum number of photoelectrons is required to detect a pulse, and the 1550 nm photon has half the energy of a 780 nm photon, we see that, for the same (electronic) preamplifier noise, an optical pulse at 1550 nm can be detected with ~ 3 dB less optical power.

## 4. COMMERCIAL INFRASTRUCTURE

In addition to the advantages discussed in the preceding sections, which are grounded in fundamental physical principles, operation at wavelengths near 1550 nm also offers other significant advantages to an optical wireless system. Since this is the wavelength range most commonly specified for terrestrial fiber-based optical communications, the supporting technical infrastructure for this wavelength range (such as a wide selection of passive components, signal generators, practical optical amplifiers, and receiver photodetectors) is vast and growing rapidly every year due to the multi-billion dollar annual investment being made. Also, the intense cost competition that characterizes the fiber communications industry ensures that 1550 nm-based systems will always be able to access new cost-effective technologies offering improved performance. The ready availability of this vast commercial infrastructure is the key factor ensuring that 1550 nm-based optical wireless systems can always grow along with the fiber-based networks of which they are a critical element.

As a representative example of the advantages of 1550 nm-based systems that are due to the available commercial infrastructure, consider trades associated with transmitters, specifically the maximum modulation rate and the cost. It is well known in the telecommunications industry that 1550 nm diode lasers are widely available that can operate at 2.5 Gbps, with devices capable of 10 Gbps operation also beginning to appear. By contrast, the highest data rate possible with commercial 785 nm diode lasers is ~ 622 Mbps, with minimal industry effort planned to extend this bandwidth capability. Moreover, the wide availability of WDM components for 1550 nm systems opens up a straightforward approach for scaling to higher throughputs, while using standard commercial components. Such commercial components are not available for devices in the 780 to 850 nm spectral range. Finally, as was stated in the introduction, one of the expected advantages of 780 nm diodes is the anticipated low cost due to the high volumes manufactured for CD recorders. This expectation is not necessarily justified, however, since 1550 nm diode lasers also enjoy very high volumes. In fact, we have been able to co-develop a 1550 nm telecommunications-grade diode laser with approximately the same cost per transmitted mW as for a 780 nm diode.

## 5. CONCLUSION

The access network performs a critical function in the overall telecommunications network by bridging the “last mile,” and thereby providing a cost-effective means for users to utilize the network and its broad array of services. Among the emerging access technologies, one of the most promising is optical wireless, since it offers fiber-like bandwidth and the lowest cost per bit of information. In order to successfully design and field an optical wireless system, a number of critical design trades must be resolved. One of the most significant trades concerns the specification of the optical wavelength. Despite the fact the most of the early optical wireless systems employed wavelengths in the near-visible infrared spectral region (~ 780 nm to ~ 850 nm), for a number of reasons a better choice is to use wavelengths near 1550 nm. Eye-safety regulations permit ~ 50 times more transmitted power at 1550 nm than 800 nm, which directly improves penetration through fog – the principal atmospheric challenge confronting optical wireless. Moreover, we have found that this higher power can be achieved at comparable cost (dollars / mW) as the sources in the shorter wavelength range. Comparable receivers enjoy approximately 3 dB better receiver sensitivity at 1550nm due to the lower energy per photon. And finally, the multi-billion dollar annual investment in 1550 nm technology infrastructure ensures the long-term scalability of 1550 nm optical wireless systems.