

Efficiency of Optical Signal Transmission and Processing

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ABSTRACT

Engineers and bankers measure efficiency differently; this is reasonable since their performance is measured differently. This analogy alludes to the many ways in which optical transmission and processing efficiency are measured. Efficiency is measured by the user, and can be optimized for one or a few metrics at once. It has been theoretically established that optical data transmission is more efficient than electrical data transmission, in units of energy per bit. Use of optical fiber and networking techniques open the potential of greatly increased speed and capacity. The telecommunications and computer industries are leading the way in use of new technology. The avionics industry follows, fulfilling more stringent environmental and reliability requirements. Inclusion of other types of constraints can sometimes confound observed efficiencies based solely on optical performance.

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IMPORTANCE OF EFFICIENCY

It was once easy to measure the energy cost of data transmission. Just weigh your favorite book, and just measure how tired you get while carrying it around! Nowadays you may not need a book; you may need a piece of information, but need to search for it using a laptop or handheld computer and the internet. This in itself is tremendously flexible and costs next to nothing. Unfortunately we have the capacity to measure the energy cost when this activity accumulates among millions of people over billions of instances.

In the present information age, we sometimes do not realize that information we transmit, process, store, retrieve, and replace, has a cost in terms of energy. Our use of 1) computers, 2) networks that transmit information, and 3) local or global data centers that process information, have made the cost of handling of information negligible compared to information stored on paper. The cost of this commoditized "electronic" information, compared to paper information, is next to zero. But now, we depend on immense amounts of information to be available at our fingertips. The paradigm of carefully organized paper files of information has been replaced by collections of data that can be flexibly and resiliently searched. The methods that we use every day to transmit, process, and use data have changed completely. Although the rate of network growth is slowing, transfer of information grows at 40% per year, and the power generated to drive it is increasing by only 3% per year [1]. Aggregate

transmission and processing of information for the world is now a noticeable part of our overall use of energy.

Basic measurement of data transmission and processing begins with a model of a basic transmission link. A bit- the fundamental unit of information- is carried from an origin to a destination. It can be processed along the way, influenced by contributing information. However the efficiency of fundamental data transmission is measured in terms of energy per bit. Theoretically, it takes less energy to move an optical bit than an electrical bit, so optical data transmission and processing will become more popular as it becomes more technically feasible [2]. In an optical network, the bit is in the form of an optical pulse, and is generated, transmitted, and detected. These three functions are covered in more detail below:

- Generation of an optical bit is done by an optical source. A bit usually begins as an electrical pulse which must be converted to an optical pulse. Light is created by Light Emitting Diodes (LEDs) or by Laser Diodes. It can be formed into an optical pulse by the device itself or through use of an external modulator. The energy per bit for an 850 nm LED operating in the data frequency range of 100 megahertz (MHz) is roughly 1 picojoule (pJ); this is a typical approach for a low frequency driver for multimode fiber. The energy per bit for Dense Wavelength Division Multiplexed (DWDM) sources using heavily loaded single mode fiber is in the tens of femtojoules (fJ) [3].

- Transmission of an optical bit can be done via free space, optical waveguide, or optical fiber. Here, optical transmission has an advantage over electrical transmission. Loss or attenuation in transmission media is wasted energy, dissipated as heat or misdirected away from the destination. The attenuation of optical fiber in particular is orders of magnitude less than electrical wire or coaxial cable, and is often measured in units of decibels per kilometer (dB-km). The frequency response of optical fiber, using light sources with modulated signals, is also very large compared to the response of electrical wire, waveguide or coaxial cable [4, 5]. The frequency response and bandwidth of optical fiber is often limited by the driving electronics.

- Detection of a light pulse is done by a photodetector and its associated receiver. From an optical transmission view, efficiency of the photodetector is measured as the energy required to charge the photodetector capacitance which is normally in the range of several femtofarads (fF). For commonly used photodetectors, this is normally in the range of femtojoules per bit.

The efficiency figures above are state-of-the-art; total data transmission energy for a transmitted bit would be under one picojoule, and processing efficiency would be not much more. Commercial businesses involved in information processing are certainly more apt to measure their business performance in correlation with information processing efficiency. Those businesses, whose performance is measured using a small number of financial metrics, are able to improve performance faster and more flexibly than a business that is highly regulated and measured in other ways. For example, businesses whose technology refresh cycle is long would be concerned about reliability and life cycle cost [6]. Even in making decisions about data transmission and processing efficiency, measurements can be confounded by hard constraints and metrics that appear to conflict. This paper will attempt to illustrate some of the interactions that govern the efficiency of optical networks and transmission systems, and why common network performance is far worse.

Fundamental Tradeoffs in Efficiency

The Size and Weight Argument

For any platform that uses energy to move, size and weight are quite important. The size and weight tradeoff with energy use brings up the pinnacle of optical transmission link design- the transition of electrical signal transmission to optical. This example is key when considering whether optical data transmission is feasible for a system. Adding an optical fiber link in place of an electrical link for a single channel may involve adding optical-to-electrical converters at each end of the link, and replacing electrical cable with optical fiber in between. The governing relationship is shown in [equation \(1\)](#) below.

$$\text{Weight or space of electrical cable} > \text{Weight or space of fiber optic cable plus transceivers} \quad (1)$$

The relationship works for weight or space. According to the equation, if the weight or space of the electrical cable exceeds the combined weight or space of the fiber optic cable plus transceivers, use of optical transmission is a good choice. This is illustrated in the [Figure 1](#) below.

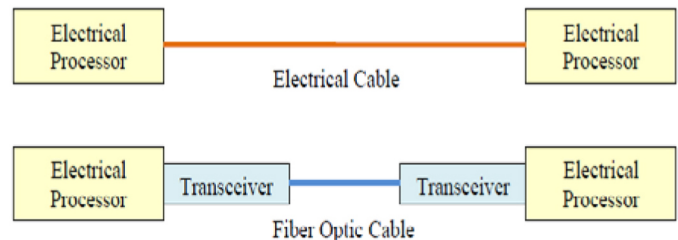


Figure 1. Illustration of Equation (1). The top shows an electrical link and the bottom show a fiber optic link.

The bottom illustration resembles an active optical cable. Active optical cables are sold as products which connect standard electrical interfaces, but contain their own electrical-to-optical conversion optics and fiber optic cable. Active optical cables use the benefits of low optical fiber loss and low fiber weight to justify their replacement for electrical links; active optical cables are available from several suppliers [7, 8, 9].

As more processing functions and levels of packaging accommodate optical signals, the easier the decision to use optical signal transmission is to make. Many developers of photonic integrated circuits will increase the role of light in data transmission to higher level functions, beginning with sensing and filtering, on to data conversion and optical computing.

Physical Tolerances for Multimode Fiber

Two fundamental types of optical fiber are commonly used:

- Single Mode Fiber- only one mode is allowed to propagate. Standard single mode fiber, or SMF, is made to transmit light in a single mode in a wavelength region around 1550 nanometers. The core of this fiber is roughly 8-10 microns in diameter. Single mode fiber is used most often when many signals are sent through a single fiber at once using Wavelength Division Multiplexing (WDM). Single mode fibers are capable of carrying signals with high modulation frequencies over long distances.

- Multimode Fiber- multiple modes are allowed to propagate. Standard commercial multimode fiber transmits light around 1000 nanometers. The core diameter of commercial multimode fiber is 62.5 microns, although special multimode fibers are available with core diameters from 50 to 400 microns in diameter. Multimode fiber is normally used to carry a single optical signal at low modulation frequencies for short distances.

The essence of this tradeoff in efficiency is that multimode fiber, with its larger core diameter, has less