Parallel WDM Transmission for Ultra-high Bandwidth

STAMATIOS V. KARTALOPOULOS
Williams Professor in Telecommunications Networking
ECE Depertment, TCOM graduate program
The University of Oklahoma
4502 E. 41st Street, Tulsa, OK 74135, USA

Abstract: - Wavelength Division Multiplexing (WDM) is a technology that multiplexes a number of optical signals in a single optical fiber achieving very high aggregate bandwidth. Each optical signal provides a bitrate well above 1 Gbit/s, and thus the aggregate information capacity per fiber exceeds Tbit/s. This technology is also formidable for inter-computer communication where ultra-high bandwidth needs to be transported from computer to computer and within a cluster and where redundancy or parallel computation is required. However, as the bit rate increases, the link complexity increases as well as cost, both of which are very critical in computer applications. In this paper we present a WDM parallel transport method by which ultra-high bandwidth is achieved yet with low modulation bit-rates, low power source lasers and low complexity. This method also minimizes dispersion and non-linear phenomena, it does not degrade the quality of signal, it increases transmission reliability and it reduces cost per transported bandwidth in short and in medium-haul.

Key-Words: - Supercomputing networks, Ultra-high rates, Wavelength-bus, optical computer networks

1 Introduction

Wavelength Division Multiplexing (WDM) is a physical-layer technology that multiplexes many optical signals, each at different wavelength, for data transport over a single optical fiber. Recent advances in optical technology allow for dense wavelength division multiplexing (DWDM) with as many as 160 channels in the C and L bands, and bit rates up to 40 Gbit/s per channel [1].

In WDM systems, the aggregate bandwidth per fiber is the product number of channels (wavelengths) times the bit rate per channel. In fiber-optic communications, it is established that at bit rates up to 2.5 Gbit/s and for a given length of fiber, the two dominant limiting factors are chromatic dispersion and fiber attenuation, which at this data rate and for all practical purposes may be considered linear. In addition, secondary phenomena, such as polarization mode dispersion (PMD), polarization dependent loss (PDL), and dispersion slope play an insignificant role regarding the quality of the transmitted signal. In fact, the chromatic contribution as a function of bit rate is established as [2]:

=> From 2.5 to 10 Gbit/s the chromatic dispersion increases 16 times.
=> From 10 to 40 Gbit/s the chromatic dispersion increases 16 times.
=> This trend continues for 40 Gbit/s to 160 Gbit/s?

It has also been established that at 2.5 Gbit/s and for short and medium single mode fiber lengths (<100 km), amplification may not be important [3]. Particularly, in parallel computation or in redundant clusters, the link length is typically below one kilometer length and thus fiber length is not as important although for all practical purposes the transportable bandwidth is. In this paper, we present a WDM method to transport ultra-high bandwidth over fiber using low data rates per optical channel.

2 The Wavelength-Bus

2.1 Bandwidth elasticity

In WDM, the fiber is a transporting medium and the wavelengths in it carry independent and uncorrelated serial bit-streams. Assume that we bundle the wavelengths so that each bundle consists of eight wavelengths (in theory, it can be any number). Fig.1 illustrates an example of a generalized WDM channel organization of data with eight channels (λ1 to λ8) and Fig.2 a simplistic WDM point to point link.

λ_1: a10 a11 a12 a13 a14 a15 a16 a17 b10 b11 … b15 b16 b17 c10 …
λ_2: k20 k21 k22 k23 k24 k25 k26 k27 … a20 a21 a21 a23 a24 a25...
λ_3: m30 m31 m32 m33 m34 m35 m36 m37 ... a31 a31 a33 a34 a35..
.. : ....
λ8: p80 p81 p82 p83 p84 p85 p86 p87 … a80 a81 a81 a83 a84 a85..

Fig.1: A generalized DWDM multi-channel organization

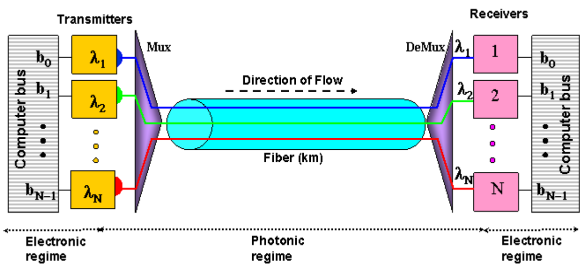

Fig.2: A simplistic WDM point-to-point link

In a general case, consider a multiplicity of *serial channels*, all *byte-synchronized*. Consider also that bytes of each serial channel are converted to parallel. We call this a *parallel channel*. In practical computer systems data is already in parallel form, and thus the conversion from serial to parallel is redundant reducing associated latency. For simplicity of description, we assume 8 bits per byte, although this is not a limiting factor.

Consider that bytes from several parallel channels are multiplexed in an orderly fashion. For 8-bit bytes this would construct an 8-bit wide bus that consists of 8 different wavelengths. Each rail of this 8-bit bus is transmitted serially at the same bit-rate with the other seven rails. We call this a *wavelength-bus*. The end result for eight serial channels (in Fig.2) converted to an eight-rail λ-bus is illustrated in Fig.3.

Stream λ1: a10 k20 m30 … p80 b10 ...
Stream λ2: a11 k21 m31 … p81 b11 ...
Stream λ3: a12 k22 m32 … p82 b12 ...
Stream λ4: a13 k23 m33 … p83 b13 ...
Stream λ5: a14 k24 m34 … p84 b14 ...
Stream λ6: a15 k25 m35 … p85 b15 ...
Stream λ7: a16 k26 m36 … p86 b16 ...
Stream λ8: a17 k27 m37 … p87 b17 ...

Fig.3: Parallel reorganization of data on the wavelength-bus

What characterizes the wavelength-bus is its fixed transportable bandwidth. Thus, the transportable aggregate bandwidth of one or several sources needs to be less or equal to this bandwidth. As an example, 8 serial channels, each at 2.5 Gbit/s, have an aggregate bandwidth of 20 Gbit/s (as in Fig.2), whereas the required transportable bandwidth may be equal or less than that.

Consider the case of bandwidth aggregation. As an example, assume 20 data sources, each at 1 Gbit/s (i.e., an aggregate bandwidth of 20 Gbit/s). With the typical WDM case, 20 wavelengths are needed, one per source. In our case, an eight rail wavelength-bus, each rail modulated at 2.5 Gbit/s, is able to aggregate and transport these 20 sources. Thus, a wavelength-bus provides flexibility to scale bandwidth based on number of sources.

Similarly, consider that there are two data sources, each at 10 Gbit/s. In our case, these two sources may be aggregated and transported over eight wavelengths, each at 2.5 Gbit/s, a much simpler, efficient and cost effective implementation.

2.2 Short and medium-haul transport

In section 2.1, we demonstrated how many sources can be transported over fewer wavelengths, or how high data rates can be transported using lower bitrate transceivers. Clearly, if the size of the wavelength bundle was 16 or 32 (a typical size in many computer applications), then the elasticity of the wavelength-bus in bandwidth becomes more pronounced. Alternately, the bitrate per rail is further lowered. This clearly lowers the cost and increases the reliability of the link. For example, the transmitters may be LEDs instead of lasers, the link medium may be multimode instead of single mode, and in certain applications the medium may be plastic instead of glass.

The wavelength bus is also applicable in integrated photonic subsystems, where the optical interconnecting link consists of parallel optical tranceivers. In this case, each rail may be transported over separate path; however, as technology evolves, wide buses will be at a premium and rails will also be multiplexed to provide a single interconnecting WDM link.

2.4 Wavelength-bus efficiency and scalability

In the general case, the wavelength-bus can transport a single source or an aggregation of several sources. In the latter case, it is not limited to data sources of the same data rate; that is, one source is at one rate and the other at another (as shown in Fig.4). Then as sources are converted to parallel, are multiplexed and transmitted over a single fiber, the only criterion that needs to be observed is: *the aggregate bandwidth of channels cannot exceed the wavelength-bus bandwidth*. This clearly allows for different types of sources to be transported and it provides source and traffic scalability.

A wavelength bus has been modeled, simulated and transmitted over single mode fiber link at various lengths, without optical amplification and compensation. The link performance at the receiver was set to 10^{-12} bit error rate. Figure 4 illustrates the power level of three channels at center wavelengths 1552.52, 1552.32, and 1552.12 nm, for input power of 2mW (3dBm), link length of 60 km and channel separation 25 GHz. All channels met the performance objectives as shown in Fig.5.

2.4 Wavelength-bus efficiency and scalability

In the general case, the wavelength-bus can transport a single source or an aggregation of several sources. In the latter case, it is not limited to data sources of the same data rate; that is, one source is at one rate and the other at another (as shown in Fig.4). Then as sources are converted to parallel, are multiplexed and transmitted over a single fiber, the only criterion that needs to be observed is: *the aggregate bandwidth of channels cannot exceed the wavelength-bus bandwidth*. This clearly allows for different types of sources to be transported and it provides source and traffic scalability.

A wavelength bus has been modeled, simulated and transmitted over single mode fiber link at various lengths, without optical amplification and compensation. The link performance at the receiver was set to 10^{-12} bit error rate. Fig.4 illustrates the power level of three channels at center wavelengths 1552.52, 1552.32, and 1552.12 nm, for input power 2mW (3dBm), link length of 60 km and channel separation 25 GHz. All channels met the performance objectives as shown in Fig.5.

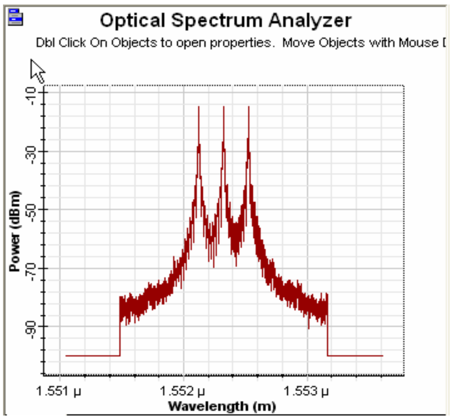

Fig.4: Power spectra of three typical wavelengths (1552.52, 1552.32, and 1552.12 nm) of the wavelength-bus; shown at the receiver.

3 DWDM Wavelength-Bus and Issues

In this section, we address certain issues pertaining to wavelength-bus systems and provide direction for solution.

Although the WDM wavelength-bus transports an ultra-high capacity bandwidth, it reduces the actual line rate and allowing for effective ultra-fast pattern recognition [4].

Because of the parallel nature of the computer bus, conversion from parallel to serial and from serial to parallel is eliminated thus reducing latency and associated buffering. In a WDM wavelength-bus system, parallel data flows from source to destination without conversions.

Protection strategies in WDM wavelength-bus systems are easily worked out by assigning "protection" wavelengths. This link protection method in Telecommunications is a well-known practice.

4 Conclusion

The WDM wavelength-bus has been presented. The case of accommodating more sources over fewer wavelength carriers has been presented, as well as the case of transporting high data rates with transceiver at a fraction of the rate.

Similarly, the bandwidth efficiency and

scalability of the WDM wavelength-bus has been illustrated. Other salient features of the WDM wavelength-bus and issues have been identified.

References:

[1] S.V. Kartalopoulos, *DWDM: Networks, Devices and Technology*, IEEE/Wiley, New York, 2003.

[2] S.V. Kartalopoulos, "Ultra-high bandwidth data transport for DWDM short, medium-haul and metro using low bit rates", *APOC 2002 Conference Records*, Optical Switching and Optical Interconnection II, Shanghai, China, October 2002, pp. 100-107.

[3] ITU-T Recommendation G.692, "Optical Interfaces for Multi-channel Systems with Optical Amplifiers", October 1998.

[4] S.V. Kartalopoulos, "Associative RAM-based CAM and its application to Broadband Communication Systems", *IEEE Trans. Neural Networks*, vol. 9, no. 5, 1998, pp. 1036-1041.

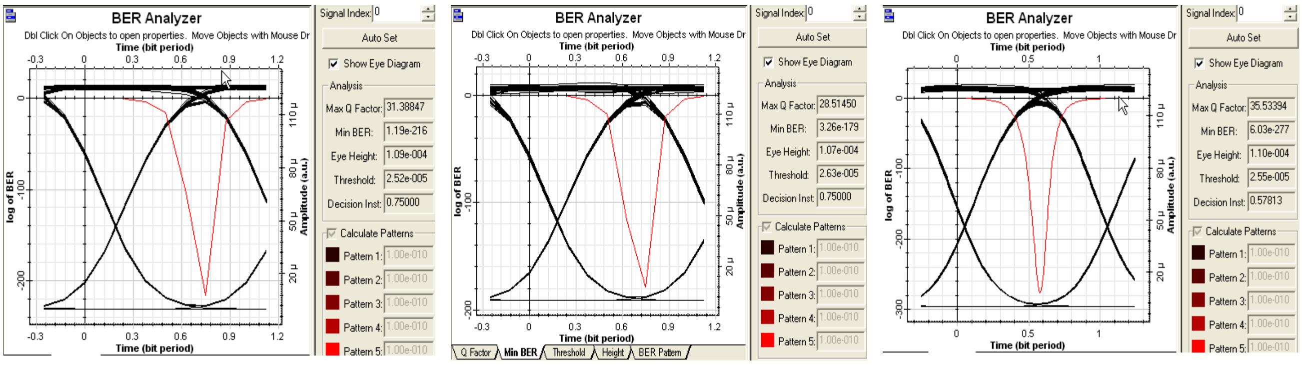

Fig.5: Eye-diagrams at the receiver of wavelengths in Fig.4.