On Physical Considerations in Design of Wavelength Grooming Optical Networks

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This paper reviews physical design issues and challenges to meet the basic premise of grooming sub-wavelength capacity traffic in all-optical networks. We discuss technology issues in areas such as all-optical time division Multiplexing, Optical pulse generation, the types of lasers for such pulses, modulators and types of amplifiers, as well as optical timing extraction for high speed optical waveform measurement. We also review some issues and experiments that have been performed to support terabits OTDM/WDM systems.

Introduction

Starting from the early 1980's the major focus of the development of the optical fiber technology is geared toward creating higher capacity, as well as longer repeater spacing. While the optical data networks are more or less new, optical communication networks have been around for a long time. The most important driving force has been the economical transmission system for communication networks. The technological contributions of the optical communication networks form the main building blocks of the optical data networks.

There has been a never-ending demand for reliable networks with higher information delivery capacities and lower costs. Based on such demands, as a logical development, optical networks have been utilized for both communication and data networks. The first optical networks were implemented to increase the bandwidth of telecommunication networks in late 1970s and early 1980sThe current solutions are based on variations of the first generation optical networks implemented for communication purposes. The first generation optical networks relied on the electronic nodes to handle all the data. The data passed through the traditional electronic switches with traditional routing functions. Intermediate switches use optical-to-electronic and electronic-to-optical conversion. Such a process is identified as an Optical-Electronic-Optical switching or OEO, where optical path is interrupted by electronic conversions, consequently the network is called opaque[1].

Typical electronic systems are much slower compared to optical systems, and thus likely to be bottleneck. The motivation for the second-generation optical systems is to route and handle optical data streams in optical domain and reduce the burden of the electronic speed. In the second gestation optical network systems, the light path is not interrupted and the information remains within the optical domain at all times. Such a system is known as a transparent optical system and is also referred to as an All Optical Network (AON). Wavelength Division Multiplexing (WDM) has been identified as one of the key technologies for the most effective utilization of the fiber bandwidth directly in the wavelength domain. The feasibility of true AONs becomes clearer by utilizing wavelengths to perform routing, switching and other network functions[1-3].

Similar to other types of networks true feasibility of the second-generation optical networks is based on the development of appropriate hardware (physical layer), software (protocol), reliability and redundancy (fault tolerance), traffic grooming (wavelength sharing), and security (network monitoring, identification, localization, and capturing of the intrusion). Consequently, technological developments such as wavelength conversion, fast and reliable all optical 2 and 3 dimensional switches, optical amplifiers, and other all optical components, systems, and interconnects have been attractive for the 2^{nd} generation optical system. In addition developments of access schemes for local, metropolitan, and wide area networks, traffic grooming and issues of network fairness, tolerance to failures, and intelligent edge connection become major issues in the design of the second generation networks that will be replacing the first generation networks. It is important for the networks developers and designers to be aware of the major issues and available technologies as far as the physical layer are concerned. The authors have discussed the challenges at the protocol level, access schemes, grooming and fairness issues, and tolerance previously. In this paper we attempt to identify some major physical layer considerations in design of 2^{nd} generation optical networks.

The Second Generation

In the second-generation optical networks the goal is to have all-optical lightpaths from a source to a destination with no electronics interconnect except at the edges of the networks. Interfacing to other networks, such as wireless, or electronic based LANs and MANs, are defined at the edges of the optical networks.

AONs are attractive for three major reasons. First, these networks offer faster and high bandwidth application platform. The second major reason is the transparency of AONs. The desired transparency includes the light path transparency as well as transparency to protocol and data type. Transparency to protocol and data types make the expansion and reconfiguration of AONs easily achievable. In addition as new applications and communication schemes are introduced in the industry, the transparency becomes more important. Finally, since there is no mixed signal (electronics/optical) the second-generation networks also offer an economical solution due to their ease of operation and maintenance to the users and service provided. Based on these major characteristics, AONs are a great alternative for the future optical networks.

It should be noted that as the utilization of the optical networks increases and more commercial, sensitive, private, as well as public forms of data and information are put on these networks, the need for a robust secure, and stable networks increase. While currently the security is a debated issue and in many cases is considered users' responsibility, in the future optical networks security and reliability will be highly demanded at all network levels. We believe that the type of desired security and robustness will be compatible if not superior to the current sensitive and national defense type networks. Designers of the second-generation optical networks need to also consider such relevant issues. Some of the more interesting and challenging issues are to maintain the reliability, security, resource fairness, and effective operation in a heterogeneous environment of optical networks with wireless, ad hoc, flexible form networks, and other electronic based area networks at the user end of the future networks[1].

The Challenges of the 2^{nd} generation includes the hardware as well as the protocol and architecture that are applicable to LANs/MANs/WANs. The LANs are the networks where fiber to the curb will be residing. The MANs are a great challenge in industrial metropolitan areas. The WANs are the true backbone of the network, where demands of the greatest capacity, reliability, and fault tolerance reside. The second-generation network will have to consider design requirements to handle all the three main networks levels[1].

The traffic management and concepts of traffic grooming at all levels are challenging and exciting issues and have been considered and summaries before[1]. Multiplexing, demultiplexing, and switching of lower-rate traffic streams onto high capacity lightpaths is referred to as *traffic grooming*. In such a situation, each lightpath typically carries many multiplexed lower-rate traffic streams. Efficient traffic grooming improves wavelength utilization and reduces equipment costs. The multiplexing and demultiplexing of the traffic streams is performed by the OADMs. Switching the traffic streams from one wavelength to another is performed by the crossconnects. The grooming of traffic can be static or dynamic. In static grooming, the source-destination pairs whose requirements are combined are pre-determined. In dynamic grooming, connection requests from different source-destination pairs are combined depending on the existing light paths at the time of request arrival[2].

The Bandwidth Consideration and WDM

Bandwidth expansion and extension has always been the goal of all communication and data networking engineers. The need for more bandwidth has been the most consistent characteristics of the network development since the beginning. The two main attempts that increase the bandwidth is to reduce the fiber losses and extend the fiber clear window. In addition, developing more precise and fine tunable components help to divide the available fiber bandwidth into smaller usable channels. Consequently, due to the special nature of the second-generation networks there is a need of special components and hardware to achieve high-bandwidth narrow-channels. Indeed the requirements for the optical components such as filters, tunable lasers, receivers, amplifiers, optical cross connect, optical add/drop and multiplexers are affected as the number of available channels increases[3-5].

For instance, as the number of wavelengths increases, we need stable, narrow-band filters, wavelength converters, specialized fiber amplifiers with reasonable flat gains over the specific bands, as well as an array of efficient practical optical cross connects that enable us to connect different optical ports, and allow for adding or dropping new wavelengths. The major items that are needed to enable WDM and DWDM network operation are

- Optical switches and cross-connects: All-optical cross connects (OXCs) and all-optical add/drop multiplexers (OADM) would make AONs feasible. The new developments in the MEMs (micro-electromechanical devices) make this enabling technology very feasible and provide great hope in reaching the all-optical networks faster[2,3]All-optical switches will not only reduce the cost of the network switching by reducing the need for transceivers, they will offer reconfigurable networks architectures, and provide faster connection and needed transparency for the AONs[1,5].
- Wavelength conversion: Wavelength conversion is one of the key technologies that will impact the future development of optical networking. Successful, economical, and practical implementation of wavelength conversion would be the most important item on the future wish list. The true transparency requires optical-optical conversions. Such converters can be used in optical interconnects, optical add/drop switches, as well as all-optical repeaters[2,4].
- Optical amplifiers and regeneration: The need for optical amplification is more obvious in the case of long haul optical networks. In long haul operation signals weaken due to the large distances and there is a need for amplification to make sure

the right signal level reaches the receivers. Currently optoelectronic amplifications offer 3R solution. 3R and 2R solutions are desirable for high-speed networks and are being studied[5].

- Optical electronic interconnect: Optical-electronic interconnection is a necessary technology that makes the fiber to the curb, fiber to the user, as well as fiber to local networks achievable. It is important to note that the 2nd generation optical networks will need to connect to different local (and even metropolitan) area networks such as the wireless and ad hoc networks that are operating at the electronic speeds. The real challenges that are to be considered are how to connect a fast speed optical fiber to a slow speed electronic network. Data loss is not an issue when the flow of information is from the electronic to the optical side as it is not likely to occur. The main concern is how to handle, provision, and find practical limits of access handling from the optical to the electronic networks without utilizing huge electronic buffers. In addition designing a fault tolerant, secure, system with redundancy needs to considered such network interconnecting and consequence of the heterogeneous environments[1-5].

TDM over WDM

All of the above mentioned enabling technologies have been suggested for WDM networks. For practical reasons the technological issues for OTDM are even more challenging. Recent advances in optical switching technology[2,5] have shown the possibility of realizing fast all-optical switches with switching times of less than a nanosecond. The use of such fast switches along with fiber delay lines as time-slot interchangers have opened up the possibility to realize optical time switched networks. These networks are referred to as WDM/TDM Switched networks. Connection between a source and destination in an WDM/TDM switched network is created by assigning a time slot on every link of a chosen path, with the constraint that the slot on one link can be switched to the next link by the intermediate node. The bandwidth granularity offered by a WDM/TDM network is determined by the duration of a time slot, which in turn depends on the speed at which the switching can be accomplished.

The thrusts for current development of systems are understandably based on fast electronic processing. However, the common belief is that while the electronic technology is not fully utilized yet, in the future eventually the electronic technology will not be sufficient and will become the bottleneck of high-speed systems. That is the reason for the new considerations for the networks of the future. Scientist and technologies believe that eventually the all-optical network will surpass all of the electronics based systems. One may ask, what are the capabilities that the future networks would need to have that would create bottlenecks in even utilizing the fast electronic systems of the future. The answer is the desire of networks that can handle over 1 Tbps (one terra bits per second). Such networks will be capable of handling a huge variety of data to huge number of users. To achieve such a high capacity and speed we need to not only work with very dense wavelength division systems (DWDM), but also utilize the optical time division modulated systems[6-10].

It is a belief that an efficient and high-speed all-optical system will be utilizing all-optical traffic grooming which is based on TDM/WDM technology. To achieve such capabilities, there is requirement for ways to create, enhance, filter, amplify and process (signal processing) very short pulses. It should also be noted that we need to create and extract in and all-optical manner with short signal capabilities that is created, transmitted, and processed in an all-optical domain. While this requirement sounds logical, it is not that easily achieved. The question is what are the main trends of technologies that are required for an all-optical OTDM/WDM networks?

Currently with the newly developed Er-doped fiber amplifier transmission of slightly over 10Gb/s are practically achievable. The question is as we require more speed and better like utilization is there going to be a point where the current technology will reach an upper limit? Is there anything that we would like to see in the technical development? The most important idea to realize is that the current 10Gb/s system still relies heavily on the electronics and OE technology. Consequently, as a natural development we can anticipate that there will be an upper limit with the current technology and the new technologies that are needed should free us from this constraint[6-7].

With the current technological needs for voice, data, picture and high-speed interaction it is anticipated that a speed of 1Tb/s is needed soon. To achieve such a speed all components of the networks needs to be revisited. We need to have high-speed technology at the nodes for processing the date and the links for controlling a low loss manageable transmission. It is important to realize that to achieve the anticipated capacity we need to have new technologies that reach beyond the current limits. The concept behind the all-optical systems is also exactly the same.

Meeting the Needs

In order to truly surpass the electronic limitations, one needs to be able to replicate certain optical capabilities in pure optical domain. While many technologies such as wavelength conversion as well as fully capable optical cross connects are needed, there are additional technologies that are required to achieve fast speed communication suitable for an all-optical system. The criteria are more restrictive when the OTDM solutions are considered. In this section we try to identify some of the major issues and technological concerns with OTDM systems. It should be noted that the OTDM requires major complicated devices that to-date have not been fully utilized for commercial implementation. In this article we hope to provide the concepts and the issues to the researchers. The technological needs can be considered the true challenge for the 2nd generation optical networks. The following identifies the major important needs and considerations[6-7].

1. Optical pulse (generation/modulation) capability
    a. Ultra short and stable optical pulse generation (in picoseconds)
2. All-optical MUX/DEMUX technologies
3. Optical transmission with soliton low loss capability (linear and nonlinear)
4. All optical repeating/all optical regeneration capability
5. All-optical timing extraction technology
6. Hi-speed optical waveform handling (measurement, filtering, general signal processing).

Figure 1 depicts the general frame and needs of an all-optical OTDM system. As one can see, the requirements are much more challenging than those for a passive WDM system. In addition due to the difficulties of all-optical signal and timing extraction handling the current trend of the implemented systems is based on OEO where the signal processing and time extraction issues at lower Gb/s are much better defined.

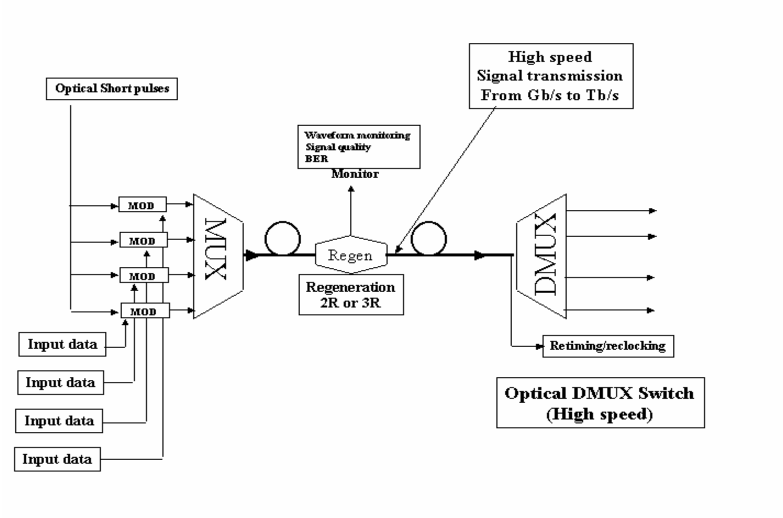


Figure 1: A block diagram of and all-optical OTDM system

In the following section we discuss some of the major developmental challenges if this area.

1. Ultra short optical pulse generation

What does it take to achieve very high speed TDM transmission? In general we need to create short pulses in order of Pico seconds or less than 5 ps pulses that are stable chirpless and transform limited. On the other hand, we also need to be able to repeat these pulses with 5 to over 20 GHz. For a broadband application of TDM we will also need to have tunable as well as precisely controllable frequencies (repetition rates). To truly optimize transmission characteristics we need to control the wavelength as well as the signal repetition speed[5].

There are various methods of optical pulse creation. However, for speeds over 10 and 20 GHz, there are only few methods that have been successfully attempted. Those include[6]

a) Gain-switching of laser diodes (of DBF laser diodes) pulses as short as 0.8 PS have been achieved
b) CW light gating with electro-absorption Modulator pulses in the order of 15 Ps have been achieved
c) Laser diode mode locking generally pulses as short as 10 ps have been achieved but in special types can go down to 1 ps
d) Harmonic Mode-Locking of EDF-lasers pulses at short as 2-3 ps have been achieved
e) Super Continuum (SC) Generation pulses less than 1 ps have been achieved.

Table 1 shows a summary of what has been demonstrated[6-7].

2. All-optical Mux/DMUX technology

We need to be able to multiplex lower digital hierarchy signals over a single path for higher hierarchical signals and also be able to separate the signals at the destinations. OTDM/WDM requires both Mux and DMux in WDM as well as in time domain. In fact the successful implementation of OTDM is based on successful and fast Mux/DMux capabilities. For the effective OTDM one should remember that DMux capability required a clock synch signal. That has lead in many interesting studies of Cock or timing recovery in all-optical systems. The literature shows high levels over 500GHz have been achieved utilizing an all-optical

Mux. One of the popular ways to achieve all-optical Multiplexing is by Four-wave mixing (FWM) in special kind of SOA (semiconductor optical amplifiers).

Off course the need to all optical demultiplexing goes hand-in-hand with the need for all optical Mux. A successful application of DMux over data and communication networks has been identified with the following items

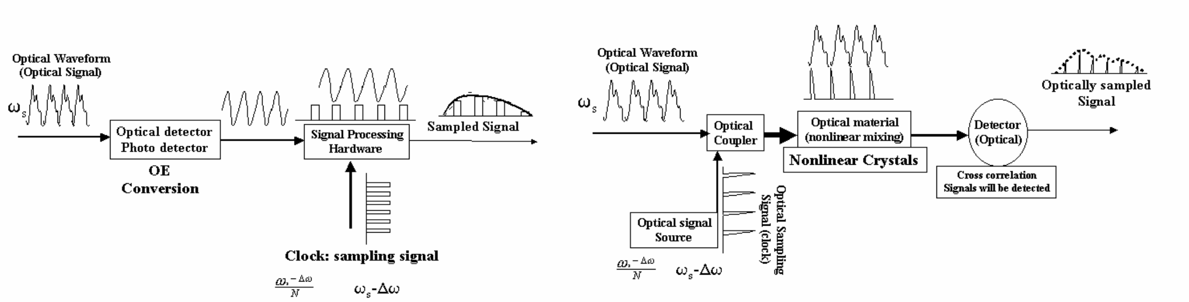
- Fast Bit Error Rate (BER) free operation
- Power stability for laser diode as well as laser pumps, i.e. Er pumps.
- Polarization independent operation
- Synchronization to the high speed received signals
- Possibility of cascading multi-output operation.

Some of the known results of all-optical demultiplexing are with optical Kerr switches that go up to 20 Gbps. The FWM-switch with 100 Gbps polarization independent operation has been achieved. Then the cross modulation phase mixing could successfully achieved 6 channels resulting to about 100Gbps. In addition, locked mirrors have also been used. Table 2 summaries what has been demonstrated in DMux technology[6].

3. Optical timing extraction technology

One of the most interesting challenges for all-optical high-speed networks is considered to be the optical timing extraction. How to extract the clock from the received signal is one of the greatest challenges of OTDM. This is essential information for repeaters and demultiplexers. The need of a clock signal is required for their correct behavior.

The system characteristics of a useful clock signal to be recovered include ultra-low phase noise, for instance less than 1 ps jitter is required for a 100GHz system. This has been one of limiting items that hinders development of faster electronic networks as well. For fast recovery and array of all-optical methods have been suggested. In general the methods are one of the following. Table 3 shows the development summary for this technology[7]



(a) (b)

Figure 2: (a) Electronic Sampling of an optical signal is limited by the photo detector bandwidth as well as the electronic sampling signal that is used. (b) Optical waveform generation can perform better than the electronic counterparts if stable and fast signals are used and the nonlinear crystal shows sufficient response.

4. Hi-speed optical waveform measurement

High speed measurement in general and in particular eye-diagram measurement is another essential feature, in order to evaluate high-speed optical transmission characteristics. All-optical sampling for measuring all-optical waveforms, and utilizing all optical gates to find the cross correlation of the sampled form and signal pulses have been demonstrated. This includes ways to handle that are sum-frequency generation (SFG) in special nonlinear crystals; XPM and Four wave mixing in fibers or selected SOAs.

Figure 2 shows a simple comparison of a optical and electronic sampling systems. Since the temporal resolution if the electronic sampling is limited by the bandwidth of the photo detector that is utilized as well as the electronic sampler that is used, one can imaging cases that optical sampling can give a better resolution. That mean in the case that the nonlinear crystal is capable of quick response to the type of signals sent to it, then the temporal resolution of the optical sampling is only limited to the signals that is used. In laboratory demonstrations timing resolution of less than 1 ps has been demonstrated.

Experimental OTDM over WDM

When one views the tedious and sensitive experiments, one may think that with all of the technical challenges it is almost impossible to have OTDM/WDM working systems. There has been more than few successful attempts proving the possibility and studying OTDM/WDM networks[7-11]

There have been a number of attempts to demonstrate different level of OTDM and OTDM-based WDM transmissions. In the area of high speed OTDM experiments at levels over 500GHz have been demonstrated and OTDM/WDM transmissions up to 3 Tbps (consists of 160 OTDM and 19 WDM) have been demonstrated. We are witnessing all increasing capabilities that are demonstrating the importance of the technology. Table 4 shows some of the developments[6-10].

Final Notes

In this paper technological challenges for the 2nd generation optical networks were briefly introduced. The main purpose is to provide the designers an appreciation of the level of the difficulties and the sophistication of the technological challenges. When considering all of the above-mentioned physical layer, and technological based challenges for the 2nd generation optical network, one is required to think about future technological predictions. Almost all of the above mentioned results are at the control environment of research laboratories. High speed, clock recovery, waveform detection and measurement are not at the state of development to be implemented in commercial systems yet. In general when dealing with the needs of all-optical OTDM in addition to being nontrivial concepts, a very high level of sophisticated setup is required for all of the proposed methods. This has made more than a few leaders in the industry to take the position that AONs are not really needed and perhaps will never be fully implemented. There is a great belief that we will have the OEO in one way or the other for a long time.

In the development of methods and systems that are proposed for utilization in all-optical networks there seems to be some trends that are worth mentioning. The systems that are based on semiconductor optical amplifier and nonlinear phase difference methods such as four-wave mixing seems to be showing great premise in development for components needed for WDM as well as OTDR systems[5]. In particular utilizing phase nonlinearly and FWM inside an SOA has been proposed and proven as a method for wavelength conversion as well. In addition utilization of cross gain and phase modulation in SOA in interferometer based setups have resulted in all-optical regeneration and high speed all optical logic functions. Consequently, systems based on SOAs and FWM and nonlinear phase mixing seems to have a broad band of utilization and is very promising for further development.

The authors believe that in the final analysis it will be the market needs and the commercial perspective that would accelerate the development of any new technology. The proposed methods have shortcomings and strengths. Networks architects and protocol designers need to keep being creative and proposed models assuming OTDM/WDM is fully achievable for AONs. While the designers should have a fair understanding of the technological challenges, they should not let their creative work be constraint by the speed of the progress in technological capabilities of the time. The first seeds of the future development will be found in some of the proposed designs.

Conclusions

In conclusion we demonstrated the major issues of the 2nd generation of all-optical networks. In this article we also focused on a review of the major technological consideration when TDM over WDM is considered for all-optical systems. We have presented the major technological challenges for TDM together with some experimental systems that were tested and demonstrated.

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Table 1: Optical pulse generation for making short pulses

Generation Method	**Characteristics**	**Duration in Pico seconds**	**Comments**
SC generation	Tunable Freq. Needs pump freq	<20	Can get less than 20 ps with the right method Also can get about 1 ps with pulse compression
Harmonic mode locking of EDF laser	Tunable Freq. Requires mode locker	15	Large pulse width
Mode Locking	Fixed freq.	10	Conventional way Use CPM or EA modulator can get down to 1 s
EA modulator	CW arbitrary Freq.	3	Tunable wavelength
Gain Switching	Arbitrary	1	Tunable wavelength
DFB mode lock.	CW frequency	6	Laser sees sel phase modulation

Table 2. Demultiplexing all optical DMUX

Method	**Utilization**	**Bit rate in Gb/s**	Date reported
Optical Kerr switch		Up to 60 reported	92
FWM switch	In fiber	100	94
		Up to 500	96 free BER
	In SOA	100	94
		200	96
XPM switches		100	97 BER free and with multiple channels
Loop Mirror switches	NOLM	Up to 640	98 BER free
	SLALOM	80	98 BER free operation
	TOAD	160	94 BER free operation

Table 3. Optical high speed timing extraction

Method	**Utilization**	**Speed in Gb/s**	**Date reported**
Tank circuits	Fabry-Perot Etalon	2	92
	Fiber based Brillouin gain	5	93
Injection Locking	Self-pulsation in DFB	10-18	93-99
	Mode-locked laser diode	10	95
	Mode like fiber laser	20, 40	94, 93
PLL (Phase lock loop)	Electrical	40	93
	LiNbO3 (external)	14	92
	TW-SOA Gain modulation	50	93
	FWM in TW-SOA	200-400	94-95
	FWM in Fiber	20	93

Table 4: some of the recent all optical OTDM/WDM reported successes

Pulse-width (signal) Ps	MUX	DMUX Speed in Gb/s	Fiber path length in Km	Method and Speed in GHz	Total bit rate Gbps	Date Reported
PM-SC pulses of 2.1	16 OTDM/19 WDM	FWM 160 Control: SC 35	40 no repeater	FWM 160	3000	99
SC-pulse 2.1	20 OTDM/7WDM	FWM 200 Control: SC 3.5	50 no repeater	FWM 200	1400	98
SC-pulse 3.5	10 OTDM 10 WDM	FWM 100 Control: SC 3.5	500 11 repeaters	PI-FWM 100	1000	96