Chapter 1

Introduction

1.1 Overview and current scenario in lightwave networks

With the rapid growth in the information consumption and emerging new services and applications such as multimedia, supercomputing, medical imaging etc., there is a strong need for high speed communication networks infrastructure capable of handling higher transmission speeds, larger user populations and higher throughput per user. Optical fiber based lightwave networks and systems and their enhanced versions with appropriate technology decidedly hold the promise of providing the deemed infrastructure.

One can identify three generations of networks based on underlying physical level technology employed. The networks based on copper wire or microwave transmission (i.e. built before the emergence of fiber optic technology) are referred to as the first generation networks. Their examples include Ethernet (and subsequent IEEE 802.3), IEEE 802.4 token bus, IEEE 802.5 token ring, Cambridge ring, ARPANET, IBM's system network architecture (SNA), and Digital's digital network architecture (DNA).

The second-generation networks employ fiber in the traditional architectures. Their examples include the synchronous optical network (SONET), the fiber distributed data interface (FDDI) ring networks and the IEEE 802.6 distributed queue dual bus (DQDB) for local area network/metropolitan area network (LAN/MAN), the broadband integrated services digital network (BISDN), and the upgrade of long-haul trunks in a wide area network (WAN) from copper or microwave radio to fiber connections. Although some improvement in performance can be achieved by employing fiber (e.g., higher data rates , lower error rates, and reduced electromagnetic emission from cabling), the limitation of this generation can not fully access the enormous fiber bandwidth (≈ 30 THz) due to the electronic bottlenecks in the front end at the network nodes.

In the third-generation networks, fiber is used because of its *unique* properties. To exploit the unique properties of fibers in order to meet the needs of emerging high-bandwidth applications, totally new approaches are employed in these networks. In these networks, the information may remain in the optical domain (and may not face any electronic bottlenecks) once it enters into the network, until it is delivered to its destination. Ideally, the third generation networks should provide an aggregate throughput that scales linearly with the number of users, and whose maximum aggregate throughput approaches the product of the number of individual users and the maximum rate of data transfer across the electro-optical interface (i.e., about 1 Gb/s).

The high capacity requirement can be attained by using concurrency among multiple-user transmissions into the network architectures and protocols. In an all-optical network concurrency may be provided according to either wavelength or frequency (WDMA : wavelength division multiple access, FDMA : frequency division multiple access), time slots (TDMA : time division multiple access) or waveshape (CDMA : code division multiple access). Both TDMA and CDMA need node synchronization and, therefore, are less attractive compared to WDMA. The WDMA on the other hand has excellent features in a networking environment and employs mostly the existing technologies (e.g., intensity modulated receivers at the end user's equipment) and the individual channels are expected to operate at the peak electronics speed.

Most of the wavelength division multiplexing (WDM) lightwave networks can be defined as either *broadcast-and-select* networks or *wavelength routed* networks, and each in turn can be either *single-hop* or *multihop*. The unnecessary splitting loss and lack of wavelength reuse in broadcast-and-select networks prevent these networks from being scalable, due to linear dependency of the power loss and the number of wavelengths on the number of users. The dynamically reconfigurable wavelength routing network consists of a number of routing nodes connected by optical fibers in a regular topology or in an arbitrary topology.

The node performs *routing* i.e., directing signal power to selected destinations over prescribed paths and *multiplexing* i.e., combining signals from several users to set up connections by creating an optical signal path from source to destination. These functions are performed by *wavelength selective switches*. Since these switches can independently switch different wavelengths, it is possible to confine selected wavelengths to limited regions of a large network, thereby creating the opportunity for wavelength reuse in other parts of the network. The controllable wavelength selective switch executes optical signal routing and multiplexing in a dynamic fashion making the network to adapt to changing network conditions e.g., network load variations, node and link failures, etc.

A distinctive feature of a WDM network is that it possess both a *physical topology* and a *logical topology*, and its logical topology defines the logical interconnection of stations, which can be specified independently of its physical topology. Furthermore, when wavelength-agile transceivers are used, the logical topology can be reconfigured to allow the network to adapt to the changes in the traffic load or to the component failures. The WDM can considerably simplify the physical interconnections between the network nodes and permit the construction of centralized hubs. By employing high-speed transmitters (lasers) and receivers (filters), dense WDM may also be used for circuit-switching and packet-switching as well as for wavelength routing. In general, nearly arbitrary (regular or irregular) virtual network topologies can be constructed for any given physical topology of the network. Obviously, the optimality of the virtual topology will be governed by the offered pattern of network loading (the traffic matrix).

In a multihop packet-switching network, the basic function is the routing of packets from their source to their proper destination. This operation has to be performed keeping the transmission delay and the packet loss as low as possible. The different taxonomies of routing algorithms are possible, e.g., *static* versus *adaptive* or *centralized* versus *distributed*. They may be put into two groups, namely, *table-based routing* and *self-routing*. The first class covers most of the traditional approaches that have been applied to many slow networks, including shortest-path routing and optimal routing. Aside from other problems, as the convergence delays are proportional to the network diameter and have susceptibility to oscillations, these algorithms are computationally expensive and require a substantial amount of book-keeping and periodic transmission of status information among the nodes. In the case of self-routing, the routing decision is solely made based on information extracted from the packet's header, typically the destination address. Most of multiprocessor interconnection networks use this scheme (e.g., shuffle-exchange network, hypercubes, data manipulator networks, Benes networks, and Clos networks).

It is possible for more than one packet to opt for the same outgoing link at the same time. In such a case, the node has to decide what to do with the packet (or packets) that can not be immediately relayed on their preferred links. Such a packet can be either buffered until the link becomes available or it can be relayed on another (available) link along a sub-optimal path to the destination. The former case is called *store-and-forward* routing and in the later case, we say that the packet has been *deflected*. The deflection routing is possible for networks with limited or non-existent buffer space at the nodes. Generally, buffering of transient packets at intermediate switches has a number of disadvantages which are amplified when the network operates at a very high transmission rate. Networks with large (practically infinite) memory switches are as susceptible to congestion as networks with low memory switches. In the former case, the queueing delays can get so long that by the time packets come out of the switch, most of them may have been already retransmitted by the higher layers due to time-outs.

The existing installed fiber plants use mostly dispersive standard single mode fiber widely using 1550 nm window. The main objective in the short term is to minimize the amount of fiber to be laid, to increase the capacity, and to increase the non-regenerated fiber spans. Amongst the various options available to achieve higher capacity, N×R WDM systems, where N is equal to the number of WDM channels and R is the per-channel (typical, R=2.5 Gb/s) bit rate, are still attractive, as such systems are tolerant towards chromatic dispersion as well as polarization mode dispersion. However, with increasing value of N, the impact of dispersion slope and other nonlinear effects (four-wave-mixing (FWM), cross phase modulation (XPM) etc.) are of significant importance.

Although a significant progress has been achieved in long distance high capacity point-to-point links, the progressive demand for high performance, high capacity communication network infrastructure bringing the benefits of high speed multimedia and other services to large and small users alike is severely felt. The multiwavelength multihop network creates essentially the optical pipes over existing fibers to allow

- increased connectivity among 'access stations' at least cost
- to (re) configure connectivity on fixed physical topology
- to create alternate routes for enhanced reliability
- to introduce service channels for monitoring/control
- to perform space/wavelength routing of express traffic
- to avoid DXC (digital cross-connect) size and cost explosion
- to lighten the management load
- to enable best protection/restoration mechanism
- to provide bit rate/signal format transparency
- to avoid hardware multiplication/replacement

The evolutionary path for the future WDM networking conceptualizes a layered structure consisting of a WDM photonic layer, synchronous digital hierarchy (SDH) electronic layer, and asynchronous transfer mode (ATM) electronic layer. The photonic layer handles semi-permanent wavelength channels using optical cross-connects (OXC) and optical add-and-drop multiplexers (OADM). The SDH layer handles semi-permanent synchronous virtual containers using digital cross-connects. The ATM electronic layer handles semipermanent or switched asynchronous virtual connections (cells).

The photonic layer implementation follows broadly two approaches : wavelength routing (wavelength path concept) and wavelength translation (virtual wavelength path concept). The wavelength routing approach has the following features:

- each optical path is assigned a single wavelength from end-to-end
- wavelength is reused on fully disjoint routes
- wavelength blocking is avoided by global routing/wavelength assignment

Similarly, the following are the main attributes of the wavelength translation approach :

- wavelength is a physical resource, reused and assigned link by link
- each optical path is assigned a concatenation of wavelengths
- wavelength blocking is avoided by wavelength translation (conversion)

Both the above approaches have their individual merits and demerits. However, the choice between the two will depend on meeting the ease of network administration, degree of transparency required, complexity of node architecture, required number of wavelengths etc.

A considerable progress has been achieved with regard to the development of the key functional blocks and routing systems such as the fixed and reconfigurable optical OADM/OXC based on space switches, tunable filters, wavelength converters etc. However, the main goal is to achieve multi-cast capability, upgradibility, modular growth capacity (in terms of number of fibers and number of wavelengths), multi-bit-rate and multi-format transparency, cascadability and high throughput. The above developments lead to several successful multiwavelength networks demonstration projects and field trials such as multiwavelength transport network (MWTN) within Europe and multiwavelength optical network (MONET) in USA and optical path network (OPN) in NTT, Japan. It appears from the current trends that the deployment of WDM transmission technology with upto 32 wavelengths with per wavelength capacity of 10 Gb/s, for point-to- point link as well as in wavelength routed network would become possible before the end of the decade.[1]

Active research work is already underway in lightwave networks around the world to explore these concepts to satisfy the emerging needs for broad-band multimedia telecommunications through proper choice of network topologies, switch architectures, multiaccess schemes, media-access protocols etc. [1, 2, 3, 4, 5, 6, 7, 8, 9]. Regular topologies that have been studied as candidates for multihop lightwave networks include the perfect shuffle [10, 11, 12], the de Bruijn graph [13], the Manhattan street network (MSN) [14, 15], and the hypercube (HC) [16, 17]. The MSN was one of the earliest high-performance MANs to be based on lightwave technology.

The performance of the regular multihop lightwave networks have been studied under deflection routing scheme [15, 18, 19, 20, 21, 22, 23, 24, 25]. Multichannel local lightwave networks with grouping properties are discussed at length in [26]. An efficient routing scheme for scalable hierarchical networks has been studied [27]. Gu and Peng [28] have studied the fault tolerant properties of n-dimensional hypercubes for routing problems. In an wavelength-routed optical network, the performance improvement achievable with wavelength converter is an important issue which attracts sufficient research interest at the present time. Most of the published work [29, 30, 31] deals with circuit-switched networks to determine analytically as well as by simulation the actual requirements of the number of converters, placement of wavelength converters, providing partial or full wavelength converting facility etc. to achieve the desired blocking error probability performance. The benefit of wavelength converter in a packet-switched wavelength routed network however, needs more investigations.

1.2 Technical issues

The high capacity packet-switched networks operable over longer distances as in MAN and WAN must have to overcome the transmission limitations of the fiber medium. The following are some of the important measures/features usually considered :

1. Deployment of Erbium doped fiber amplifier (EDFA) at regular intervals to overcome the loss induced length limitation:
2. Use of the dispersion shifted fiber (DSF) that provides longer non-regenerated system span compared to the single mode fiber (SMF) at 1550

nm.
3. Use of SMF at 1300 nm can further improve the system span. Operation with 1300 nm (with Semiconductor Optical Amplifier) and 1500 nm operation (with EDFA) simultaneously may be considered as one option in some specific application.
4. The chromatic dispersion is the dominant limiting factor in single channel system based on SMF at 1550 nm for bit rates greater than 10 Gb/s.
5. Operation close to the fiber zero dispersion wavelength for bit rates greater than 10 Gb/s needs pulse peak power not to exceed 0 dBm to avoid nonlinear pulse distortion due to self phase modulation (SPM).
6. Various kinds of dispersion management and nonlinearity management schemes.

It can be appreciated that single channel high bit rate long-haul systems necessarily have to employ either some form of dispersion compensation technique or soliton transmission. Single channel high bit rate applications employing solitons in optical network have been recently studied and the constraints of the channel, in particular, the self frequency shift timing jitter due to Raman scattering and the amplified spontaneous emission (ASE) have been taken into account while studying the performance of multihop network with deflection routing [20]. However, recognizing the present day user's interface electronics speeds capability being limited up to 10 Gb/s, the realizability of an optical network capable of providing a very high aggregate capacity of Terabit/s depends on the use of some form of channel concurrency such as the WDM mentioned before. It is, therefore, important to study the fiber channel constraints which may limit the capabilities of such WDM assisted multihop networks for packet transmission.

In MAN/WAN applications various channel impairments arise such as the FWM, accumulated ASE, XPM , inter-channel crosstalk due to non-ideal optical filtering, reflection induced crosstalk, switching crosstalk in the cross-connect node etc. All these limit the network size, the operable inter-nodal distance, the maximum number of usable WDM channels and the maximum power per channel . The above effects also induce errors in the reception of packets and therefore cause degradation in the achievable network capacity. Infact, the impact of the nonlinear effects in the fiber and the other route impairments have to be studied on the individual network basis depending on the network physical topology, logical topology, the routing scheme adopted, the hop distribution, the offered load and the traffic pattern etc. The impact of FWM, accumulated ASE and switch crosstalk in multiwavelength optical networks and possible degradation in system performance has been studied [22, 32, 33, 34].

Whatever be the photonic architectures and means of implementation, the following are some important network related issues which need to be addressed :

1. To study a number of physical layer architectures with regard to their suitability for access, inter-office, LAN, MAN and WAN environments (keeping in view the potential logical architectures that may be implemented on the physical layers). The aim is to find the appropriate size/structure/number of wavelengths etc. of the subnetwork in different environments including the channel effect.
2. To develop reconfiguration algorithm to assign wavelengths to user access pairs and to control the cross-connect switching elements to establish the approximate interconnection. These control algorithms will adapt the interconnections in response to the changing traffic pattern, specific request for circuit-switched connections and failures at optical level.
3. To make a detailed performance analysis of throughput/delay, call blocking for circuit-switched/virtual circuit-switched connections/delay versus loading performance for data packets of virtual connection or connectionless service, limitations in technology and devices.
4. To carry out network simulations study of the impact of failure mechanisms on throughput/delay performance of WDM networks for different kind of physical topology, virtual topology and routing schemes and to decide the optimum strategy that ensures the highest degree of network reliability.
5. To determine the bounds on the network size for all-optical or quasi all-optical network carrying linear/nonlinear (soliton) pulses subjected to various sources of system limitations e.g., fiber dispersion, fiber non-linearities, accumulated ASE, crosstalk, timing jitter etc.
7. An efficient wavelength allocation design for the wavelength routed network.

8. Design of an effective technique for dynamic gain equalization for amplified optical systems.
9. For networks with wavelength translation, determination of the optimum locations of wavelength converters within a network, the best way of sharing wavelength converter per fiber, per link, per node, or sharing per sub-network (partitioned networks).

1.3 Scope of present work

The present research work mainly focuses the potentiality of the WDM resources to augment the capacity enhancement and the flexibility of the well known network architectures. In particular, the network performance issues with multiwavelength operation for both circuit-switched and packet-switched applications constitute a broad scope of the work envisaged. The performance behavior of the quasi all-optical network considered depends on various routing strategies. Several well known routing strategies have been studied to indicate their relative efficiencies for the multiwavelength optical network, for both single and partitioned networks. The added flexibility and thereby the performance improvement that can be gained through wavelength translation is another important area of activity undertaken.

As explained earlier, the physical layer impairments determine in a major way the ultimate capabilities of the expected performance of a WDM network. A considerable effort is needed to analyze the impact of the various sources of physical layer impairments on the overall performance of the network simultaneously taking into account the teletraffic issues related to the dynamic behavior of the network. Such studies are expected to provide the necessary design inputs for dimensionalizing the network in terms of the optimum allocation of resources and the possible design trade off. Finally, the reliability aspects of the WDM network, in the presence of link/node failures, has been an important issue which needs a close investigation.

1.4 Thesis organization

The organization of the thesis is as follows. Chapter 2 introduces the work with some definitions and description of several regular networks and routing techniques which are subsequently used in later chapters. It also describes the WDM lightwave networks and their classifications. The rest of this chapter focuses mainly on the dynamically reconfigured wavelength routing networks. The throughput performance of multiwavelength shufflenet (MWSN) under two routing strategies with two packet injection strategies, has been evaluated by utilizing both the wavelength and space dimensions in a fully dynamic manner. The improvement in the throughput performance is indicated with inter-wavelength switching using wavelength converters.

Chapter 3 is devoted to the multiwavelength ring network. Various ring topologies such as p-ring, Smartnet, wheelnet are considered and their performances are evaluated by network simulation. In particular, the average hop, blocking probability performance (circuit-switched operation) and throughput performance (packet-switched operation) of the ring networks are determined.

The physical layer design of an wavelength routed network considering the pertinent physical channel impairments has been addressed in chapter 4. An efficient method for the computation of FWM power in a switched WDM network is presented. The maximum traversable number of nodes in a MWTN impaired by FWM, accumulated ASE and switch crosstalk is determined. The degradation in throughput performance of MWSN and multiwavelength ring network due to various channel impairments is determined following a semi-analytical approach, which combines the theoretical bit error rate analysis and the knowledge of the traffic related parameters obtained from network simulation.

In Chapter 5, we propose a novel architecture employing linked-cluster shufflenet and provide its performance analysis. The performance of this clustered network is evaluated for different network parameters to optimize the network throughput. The penalty due to the packets misrouted in the inter-cluster backbone are minimized employing suitable routing schemes.

Chapter 6 presents a reliability study of two types of multihop lightwave networks viz. the shufflenet and the hypercube. Both networks are considered with same size but with different degree. Connectivity of these networks ensures that nodes can still communicate with one another even with few links failed. We have studied the reliability performance of shufflenet and hypercube for three different routing schemes with uniform traffic. The impact of link failures on the performance of MWSN has also been investigated.

Finally, Chapter 7 provides a summary of the main contributions of the thesis and suggestions for the future research work.