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Service Survivability of Fiber Networks: Photonic Networks, SONET and ATM

Ananth Nagarajan
Victor Frost
Department of Electrical Engineering and Computer Science

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Abstract

In this report, we discuss first the importance of service survivability of fiber networks, a framework for survivability and network restoration. We discuss different methods to ensure the service survivability of fiber optic networks, at the SONET, ATM and Photonic Layers. We also present a discussion on some tools, developed at different institutions, used for simulating the design and performance of survivable networks.

Contents

List of Figures

List of Tables

1 Introduction:

Network integrity has gained prime importance with our increasing dependence on communications technology. Network failures have been known to cause tremendous and wide-spread losses to industry and affect millions of users. These losses include loss of revenue, legal losses, loss of assets, deterioration of customer relationships, loss of competitive advantage and, above all, loss of credibility[1]. Network integrity includes the important aspects of quality, reliability and survivability [3].

Survivability is defined as the capability of the network to resist interruptions/disturbance of service due to physical or natural catastrophes rather than Electromagnetic Interference or Crosstalk [1].

Survivability planning consists of the following steps [1]:

1. Prevention
2. Detection
3. Robust Design with built in protection (Self Healing)
4. Manual Restoration.

1.1 Restoration Techniques:

Tsong-Ho Wu [1] defines two basic restoration techniques : Traffic Restoration and Facility Restoration. Facility Restoration is important because it consists of fewer operations, and therefore, has the potential to restore more services in a shorter time than traffic restoration. Traffic Restoration can be further divided into Dedicated and Dynamic Facility Restoration. Features of each of these techniques will be studied in the next chapter.

1.2 Framework for Network Survivability and Restoration:

A general framework that includes and extends the existing definitions for network survivability is formulated in [13]. According to this framework, network survivability is characterized by a survivability function as opposed to a single-value survivability measure. Various quantities that can be derived from this function include the expected survivability, the worst-case survivability, the r-percentile survivability and the probability of zero survivability. This framework is based on a probabilistic analysis, by characterizing survivability in terms of S, a Random Variable. A general procedure for finding the survivability function is as follows:

1. Specify disaster type to be studied;
2. Define "goodness" of networks in terms of number of subscribers connected to a central node, or revenue collected by the network operator;

3. List the sample points $\{e\}$, or all combinations of events that may happen under the disaster type being considered;
4. Determine the survivability S_e;
5. Determine or assign probability P_e of each event e; and
6. Calculate survivability function $P[S = s]$ as :

$$P[S = s] = \sum_{S_e = s, \forall e} P_e$$

The above framework is used to define the network survivability of a centralized ring network under link failures, as an example. It is claimed that this framework provides a unified and practical approach to analyzing and designing highly survivable networks.

The above framework gives a measure of the robustness i.e. the capability to withstand failure. In the event of a failure, however, we need to ensure the recovery of the network in the minimum possible time. For this we need to define a framework for network restoration. Network restoration can be done at the Photonic, SONET or ATM layers. Each of these techniques will be discussed in the following chapters. What is presented here is a general procedure to follow in case of failure, irrespective of the level of restoration considered.

- Detect Failure: This can be done using probes, or using failure signals and/or alarms.
- Broadcast Failure Message: After detecting a failure, the failure message should be broadcast throughout the network, as quickly and as efficiently as possible. Along with this message, or following this message, another message indicating that the necessary action (like protection switching or rerouting) is going to be initiated, should be sent out.
- Begin restoration: This can be done using the various techniques to be described in this report. For instance, an alternate path may be computed, or protection switching may be initiated, or available spare capacity (redundancies) may be utilized.
- Restart normal operation: A signal indicating that the restoration has been successfully completed should be sent out, and normal operation should be resumed.

The above steps are just a basic outline. To achieve efficient restoration, more complex techniques would be required. For example, we could employ a scheme to choose the best possible alternate path, out of many available alternate paths. A very obvious way of improving the network survivability is to assign redundancies (spare capacities). It has been shown in [12] that the restorability of a network increases with the redundancy. However, it is also obvious that increasing redundancy involves increasing the cost. Therefore, a trade-off has to be made to achieve the desired measure of survivability.

1.3 Organization of this report

This report is organized as follows:
Chapter 2 deals with a brief overview of SONET, and survivable network architectures using SONET. Chapter 3 is about the Asynchronous Transfer Mode (ATM) and Restoration techniques of ATM networks. Chapter 4 deals with the exciting new field of Photonic Networks. In this chapter, we cover the advantages of Wavelength Division Multiplexing [2,6,7,8,10], different ways to design survivable optical networks, with, without and with limited Wavelength Conversion [7] and techniques for failure recovery. In Chapter 5, we deal with different simulation tools for the design and performance of survivable networks [8,9,10]. Our findings are summarized and conclusions are drawn in Chapter 6.

2 Synchronous Optical NETwork (SONET)/Synchronous Digital Hierarchy(SDH):

2.1 Overview :

Fiber-Optic systems play a very important role in today's telecommunication systems. The advantages of fibers [1] are:

- Higher capacity (Gigabit/second)
- Higher reliability (low Bit Error Ratios, free of Electromagnetic Interference (EMI) and atmospheric hazards)
- Longer repeater spacing (hence, less regenerations and therefore, less noise prone)
- Greater security (no external emission)
- Less Bulky (installable in existing conduits)
- Growth potential is unlimited (capacity constrained only by termination equipment)
- Economical (low overall system and maintenance costs)

The SDH is a universal bit-rate synchronous transmission standard derived from the SONET format. The benefits of SONET/SDH systems[1,3] are:

- Extensive provision of signal overheads intended for flexible management and control.
- It is backwards compatible with Plesiochronous Digital Hierarchy (PDH) networks.
- It can provide the physical layer support for Broadband Integrated Services Digital Network (B-ISDN), based on ATM.
- It supports multivendor environment, which simplifies interconnected and fast restoration.
- Single step multiplexing which reduces the number of redundant terminations and interfaces and increases equipment integration (in size and functionality).
- Reliability is increased because the number of network components is reduced.
- It provides a multiplexing hierarchy above DS3 for broadband services
- It reduces costs and increases remote provisioning and control capabilities of network elements (NE's) by providing faster response time in meeting customer needs.
- It allows economical dropping and insert using Add Drop Multiplexers (ADM's) without the use of back-to-back terminal configurations.
- It allows efficient and cost-effective network architectures (Digital Cross-connect Systems with Self Healing Rings, abbreviated as DCS,SHR) thus increasing survivability and services like network management.

Table 3: Rerouting Path Planning

Feature	Preplanned Rerouting	Dynamic Rerouting
System complexity	lower	higher
Network adaptation	difficult	easy
Restoration speed	faster	slower
System Reliability	lower	higher
Memory requirement	higher	lower

SONET SHR's are of two types : Unidirectional (USHR) and Bidirectional (BSHR). BSHRs can have either 4 fibers (2 working and 2 protection fibers) or just one fiber wherein half of the fiber system bandwidth is reserved for protection. The above two schemes are BSHR/4 and BSHR/2 respectively [1]. BSHR/4 can use WDM to reduce the number of fibers to 2 instead of 4. A detailed analysis of each of these architectures is given in [1].
Another SHR architecture that uses WDM is SHR/WDM [1] which requires optical components. It is easier and less expensive to upgrade and the ring size is limited only by the number of wavelengths available and not by electronics. Also Electrical to Optical Conversion (E/O) is not required if optical amplifiers are used. It has a shorter average transport delay.

2.3 Comparison of SONET survivable architectures [3] :

Attributes	**APS/DP**	**SHR/ADM**	**DCS Mesh**
Network size	2 nodes	Up to a few tens of nodes	Global
Spare capacity needed	Most	Moderate	Least
Per node cost	moderate	lowest	Highest
Fiber counts	Highest	Moderate	Moderate
Connectivity Needed	lowest	Moderate	Most
Restoration time	50 ms	50 ms	Seconds/minutes
Software Complexity	Least	Moderate	Most
Protection against major failure	Worst	Medium	Best
Planning/Operations Complexity	least	Moderate	Most

2.4 Integrated SONET Restoration Systems

A hybrid approach, employing the different restoration techniques (i.e. ring, route diversity, or mesh) and sharing the same physical transport facilities [1] provides a cost effective solution. A hierarchical restoration model suggests the following sequence (top to bottom):

- Ring/Route Diverse Protection (using APS) : used for higher priority demand.

resource allocation requests from ATM cells, calls and virtual paths have to be handled effectively to meet the specified Quality of Service(QoS). A layered switching architecture [3,4] is proposed to reduce this complexity. The network management process is simplified by classifying different types of network resources and traffic entities into layers. These layers and their functions are:

1. Facility network layer : This is the highest layer. Facility network planning is done in this layer. Survivability QoS is also taken care of partially.
2. Virtual Path layer: The VP manager configures virtual paths so that the survivability measure is optimally enhanced. It also performs fast VP restoration[4] when a failure occurs. If the VP manager is unable to maintain the desired survivability measure at a desired level due to a growth of traffic demand, the Facility network layer must initiate a facility network process. Path level recovery enables a rapid and efficient restoration and considerably reduces the complexity of traffic management.
3. Call layer: This gives the call-level QoS to the VP layer. It does admission control and dynamic call routing.
4. Cell layer : It submits the cell-level QoS to the Call manager. It takes care of Traffic enforcement, smoothing and priority buffering.

The ATM switched network alternatives [1] are:

- ATM VC-based switched network (or simply ATM switch). It is associated with call processing and path bandwidth management.
- ATM VP-based switched network (or ATM/DCS). It does not have call processing, bandwidth and routing functions, but simply transports signals transparently.
- Hybrid ATM/SONET switched network. This is discussed in [1].

Rerouting Strategies:

Whenever a failure occurs, it is possible to reroute the affected traffic using the available spare capacity, using a "capacity search algorithm". This process however is slow, and may not yield 100 percent restoration. Therefore, it is better to plan for fastest possible restoration using the frequently occurring failure conditions, by providing sufficient redundant capacity [4].

The restoration algorithms have an effect on the restoration speed of the VP's, processing and memory requirements on the nodes and the redundant capacity needed. The different algorithms considered in [4] are :

1. Local Rerouting:
   All VP's on a failed link are rerouted locally around the failed link. It is simple but it is possible that all the VP's are processed by the same set of nodes, hence, leading to a bottleneck. Besides, unnecessary assignment of redundant capacity can take place.

2. Source-based Rerouting:
   Each VP affected by a link failure is processed and rerouted individually. Thus, it reduces hop-count by looking at choices for rerouting, and selects a path with minimum redundant capacity requirements. However, memory burden on the nodes is larger and restoration time may be longer.
3. Local Destination Rerouting:
   It is a combination of the above two methods. The VP's are allowed to compute the best alternate route. Backhauling is avoided.

Different Survivable architectures using ATM are discussed in [1]. These are the ATM-VP based architectures like ATM/DCS/SHR and ATM/DCS Self Healing Mesh. The design of ATM/DCS/SHR requires the following design modules:

- ATM-SONET interface.
- Header processing.
- Service Mapping. Restoration using VP Self-healing capabilities are seen using both centralized and distributed control [2,4]. A hybrid approach combining the above control schemes is suggested [4]. This involves centralized computation of alternate paths in order to avoid large processing power requirements for nodes. After computing the alternate paths using routing tables, the central processor downloads the appropriate tables to the nodes. Each node only stores the table it needs to activate, thus increasing the speed of restoration. This hybrid approach was tested using a simulation of a failure scenario and is shown to be highly advantageous.
  Self-healing using distributed control is discussed in [2] and uses logical realization of VP's. Existing self-healing algorithms require at least one round-trip exchange of restoration messages between sender and chooser nodes (restoration pair nodes). However, in the algorithm described in [2], restoration path establishment is completed with the transmission of restoration message in only one direction.

3.3 Summary of the advantages of ATM networks

To summarize the results of the ATM network restoration experiments (carried out at NTT, Japan [2] and by Anderson et al [4] and also according to [1]):

- ATM networks have a significant improvement in restoration speed.
- Selective failure declaration and restoration, especially for soft failures, is enabled easily under ATM networks.
- Source-based routing is better than local routing.
- Multiplexing is not required for ATM networks. Hence, better network utilization is possible and capacity savings and better use of spare capacity results.

- Implementation requirements for distributed control of ATM network restoration is feasible and provides full restoration in the order of a few seconds.
- The SONET/ATM layer interconnection is expected to provide better support to survivable gigabit networks and is expected to make B-ISDN services a reality over the SONET/ATM public network.

4 Photonic Networks

Photonic Networks form the key to realizing future bandwidth-abundant transport networks. Optical technologies have been employed in the physical layer. Recent advances in Wavelength Division Multiplexing (WDM) enable up to the order of 16 wavelengths on a single optical fiber in current commercial systems. This would enable WDM to be used on the path layer. Using WDM on circuit layers would require up to 100 wavelengths on a single fiber. ATM technology provides enough flexibility to realize multimedia communication. However, the transport capability is not enough to realize wide B-ISDN. WDM is the major tool by which breakthroughs to realize high bandwidth can be realized. Optical multiplexing and routing techniques are used to reduce electronic processing bottlenecks and to allow a more efficient use of the bandwidth potential of the installed fiber-infrastructure. This chapter will cover the benefits of WDM[2], additional considerations to be made in survivable optical path design[2,6,7,8,10] and finally, a proposal for restoration of multi-wavelength networks[7].

4.1 Benefits of WDM[2]

The benefits of WDM over TDM are :

- With WDM, only that portion of the total line capacity that needs to be dropped at a node can be terminated, as opposed to termination of the entire line capacity while using TDM. This is particularly useful when the total line capacity is very large, as it minimized us of high-speed, power consuming electronic devices and also the need for serial to parallel conversion of the bit stream.
- The total throughput of the optical path cross-connect system can be much larger than that of an electrical TDM cross-connect system and the hardware can be simplified.
- Each wavelength can be logically viewed as a separate network [3], so various data formats can be transmitted over the same physical facilities. Since WDM offers the ability to multiplex several low-data rate channels, the problems associated with high-data rate systems (like OC-192) may not occur.

4.2 Optical Paths - Design and Survivability considerations

Present transport network technologies use optical technologies only to the physical media layer, for point-to-point transmission. Existing path technologies are based on electrical technologies. There are several advantages, however, to the use of optical technologies in the path layer. Optical technologies are especially important for network restoration, which is usually carried out, as seen in Chapter 3, at the path layer. Existing transfer modes have different techniques for path restoration. SONET uses digital cross connect systems(DCS). ATM networks employ VP cross-connects for restoration. When the optical path is used for restoration[2,6], a major portion of the network restoration systems will be used in common by different transfer modes, which results in the realization of more effective network restoration.

Optical paths, identified by their wavelengths, accommodate electrical paths. The optical path network uses WDM and wavelength routing. Optical paths are desired to complement existing electrical paths, and not replace all of them.

Two types of optical paths have been developed. They are the Wavelength Path (WP) and the Virtual Wavelength Path (VWP). The VWP scheme is used to allocate wavelengths link-by-link (local to a link as opposed to global). WP's use global allocation of wavelengths. Thus VWP's are similar to the VPI [6] of ATM networks. The advantages of VWP's over WP's are:

- Simple path accommodation design
- Greater flexibility in network expansion
- Fewer network resources(wavelengths or fibers) required

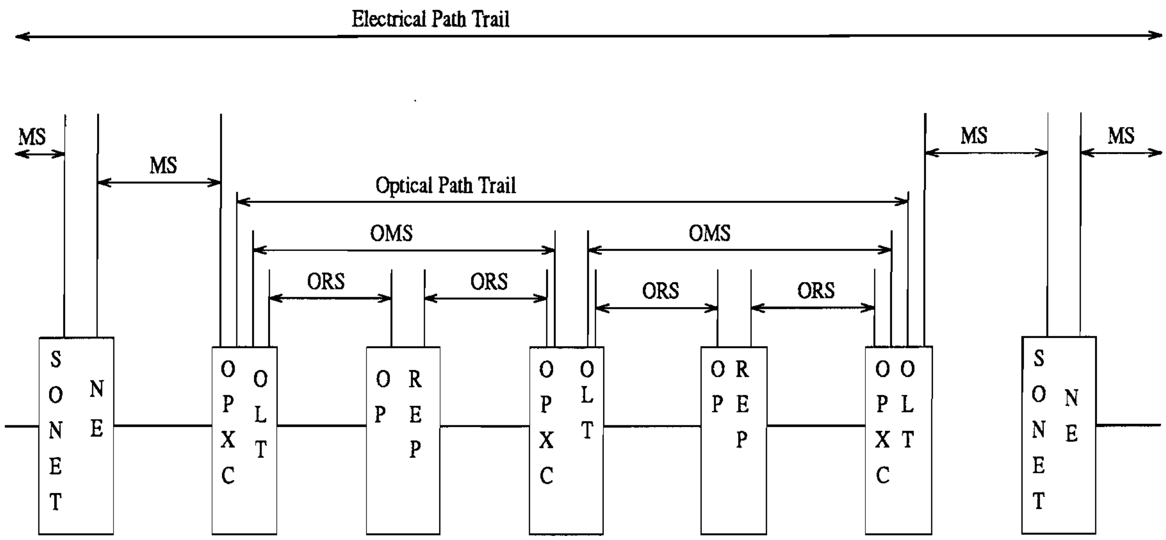
The only disadvantage of VWP is that it requires wavelength conversion at cross-connects.

The optical path cross-connect systems have the following requirements, which will, therefore, be the design goals[6]:

- The optical path cross-connect systems should be nonblocking in a strict sense to support network restoration. Blocking does not include the blocking caused by wavelength collision between input and output ports, that can occur in a WP scheme.
- Maximum modular growth capability
- Easy evolution from WP's to VWP's
- Low crosstalk and low optical loss
- Based on rather mature and credible optical technologies

Different schemes for the design of Optical paths using WP and VWP, with and without considering restoration are discussed in [6]. It is seen that VWP is definitely better in terms of number of fibers required both with and without restoration. SONET based optical path network layered architectures have been proposed. These architectures need maximum commonality with existing SONET networks for economical reasons. The SONET-based optical path networks have two sublayers: electrical path layer and optical path layer. In SONET networks, failure restoration is done with multiplex section protection and electrical path protection. In optical path networks, however, restoration will be done with optical multiplex section protection and optical path protection. This is explained below:

Optical Multiplex Section Protection and Optical Path Protection: In an optical path network, the electrical path trail, which constitutes the signals in the electrical path sublayer, is transported via optical paths. This is shown in Figure 4. Link



OMS: Optical Multiplex Section (1:1 or 1:N protection can be done here) trail
ORS: Optical Repeater Section (regenerative or nonregenerative)
OPXC/OLT: Optical Path Cross-Connect/Optical Line Terminator
SONET NE: SONET Network Element
MS: Multiplex Section

Figure 4: Network Element connection model for Optical Path Network

connection of the electrical path is provided by a multiplex section (MS) trail in the single wavelength SONET network and an optical path trail in the WDM optical path network. An optical path is terminated at the optical line terminator (OLT) which converts between the SONET and optical path signal formats. 1+1 or 1:N protection is done within the optical multiplex section layer. The unit of optical multiplex section protection is a fiber. Protection is done by switching between the working fiber to the protection fiber at very high speeds, say less than 50 ms. In 1:N or 1+1 protection discussed in Chapter 2, restoration is not effective against route failure. Besides, even restoration of a single wavelength channel due to signal loss or degradation requires that all wavelengths be switched to the protection fiber. These are avoided by optical path restoration. An optical path network proposed in [6] allows non-SONET signals to be supported by properly determining the Optical path adaptation functions specific to each electrical signal format. This scheme decreases the spare network resources needed to attain a certain level of network survivability.

The encapsulation capability of different transmission modes can be exploited to develop an effective network restoration mechanism. Line restoration and path restoration

were tested in [2]. The restoration path route was searched using a modified version of Dijkstra's algorithm and simulated. The simulation results showed that required restoration route calculation time increased almost linearly with the number of paths per fiber. It was concluded that the maximum number of paths per fiber should be less than the order of 100. This led to the conclusion that grouping of VPs is necessary for ATM networks for VP restoration. ATM optical paths[1]were compared with WP's and VWP's. It was observed in [2] that WP's and VWP's performed much better than the ATM optical paths.
In order to minimize the spare network resources to achieve a certain level of survivability, an effective Operation System (OS) needs to be developed. A likely OS called SUCCESS (Surveillance concentrated control and evaluation for SDH network) was discussed in [6]. The functions of this OS include surveillance, testing, path provisioning, and path restoration on a real-time basis against network failure.
A mathematical model to represent the routing and wavelength assignment in optical networks with or without wavelength conversion, is described in [10]. A new heuristic algorithm is also proposed to solve the routing and wavelength allocation in large WP networks. A network design tool was developed at NTT, Japan in order to evaluate the requirements of the WP and the VWP schemes in terms of path accommodation and path restoration [8]. This will be discussed in the next chapter.

4.3 Multiwavelength optical ring network[7]:

It has been stated before that the only disadvantage of VWP is the wavelength conversion involved. It is shown[11] that limited wavelength conversion is more cost-effective than full wavelength conversion. Also, if the set of lightpath requests is given in advance, very limited conversion is as good as full wavelength conversion. It has also been discussed previously that optical path restoration is better than higher-level restorations. This is because of sharing of protection channel among many working channels and also because of the different protocols supported by the lightpaths. A number of failure recovery schemes is suggested for WDM rings using limited wavelength conversion. The restoration schemes for WDM networks are different from SONET ring recovery methods because WDM nodes are based on space switching and SONET is based on time switching. However, the wavelength allocation schemes for limited wavelength conversion are more complex.
The different failure restoration schemes suggested for WDM networks in [7] are

- **Schemes for channel faults**
  These failures are to be dealt with locally, by using spare channels. Solutions for multiple channel failures are also proposed[7]. There are three solutions proposed.

[1]Optical paths are divided into two categories - one category which uses a cell/packet format to transport electrical signals. These are called ATM optical paths. The other paths are named wavelength paths/virtual wavelength paths (WPs/VWPs)

1. Allowing Full Reconfiguration:
   This solution has small overhead but requires reconfiguration of a node in case of a fault affecting all the other channels. In this method, all the channels in each point-to-point link are arranged logically in a chain. Two ports of the switch of each channel are used to connect the switch to the switch of the previous and next channels in the chain. This is shown in Figure 5.

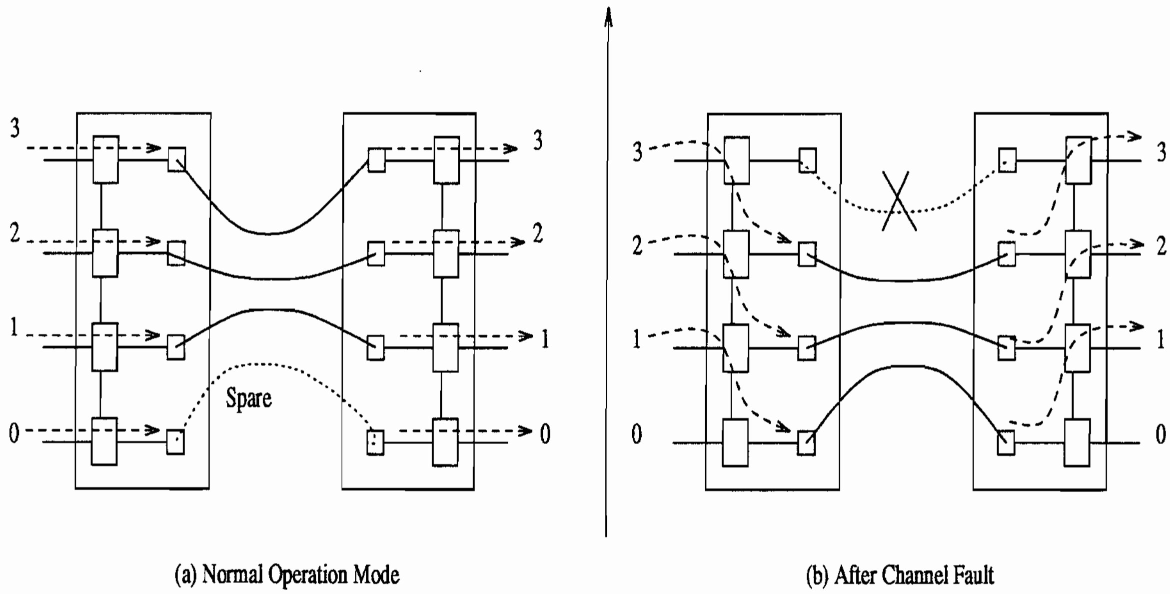


Figure 5: Protection against single channel failure using full reconfiguration

   Assume channel 0 is designated as a backup channel. If a channel i fails, the switch of i is configured to transfer i's data to channel i-1 on the link. Similarly, the switch of channel i-1 is configured to transfer data to channel i-2. This is recursively repeated till channel 1's data is transmitted on channel 0. This procedure is repeated on the other side of the link upon detection of a fault. The overheads involved in this method are:

   * Switching: Two additional ports per switch are required. These switches can be blocking.
   * Hops: Each channel goes through at most two switches in a node: its own and that of the adjacent channel.
   * Coordination: Since both ends of the link perform identical operations, no coordination is needed.

2. No Unnecessary Disconnections:
   The channels within each point-to-point link are arranged in a tree structure. The root of the tree is the backup channel and its degree is defined as the number of ports per switch that can be allocated for fault-tolerance purposes. During normal operation, each switch transfers data from its I/O port to the

link. When a channel i fails, the switches on the path from i to Backup channel b are configured to transfer i's data to b. This operation must be done without disrupting the transfer of data on the other channels from their I/O ports to the link. This requires the switch for each channel to be non-blocking. The overheads involved are:

* Switching: Given N ports are allocated for protection purposes, $N > 2$ are required for single channel protection and $N > 3$ are required for supporting up to two failures. Switches have to be non-blocking.
* Hops: Each channel goes through at most $2 + log_N W/2$ switches in a node, since one hop leads to a leaf, from which yet another hop may be necessary to arrive at the leaf of a full N degree tree containing half of the channels, leading to the currently unused spare. (W denotes the number of Wavelengths on each fiber).
* Coordination: Since both ends of the link perform identical operations, no coordination is needed.

This method requires more hardware and has longer paths to a backup channel, but requires only the faulty channel to reconfigure.

3. The third solution is integrated with link recovery and does not require additional hardware.

- **Schemes for link faults**

These are dealt with by using either a protection fiber or a loopback section. The different kinds of protection considered are span protection, line protection, online path protection and proactive path protection. It is also shown that line protection is the most advantageous and feasible solution. This mechanism is based on allocating up to half of the wavelengths for protection, with each data channel i having is unique backup channel *B(i)*. When a failure occurs at a link, it is detected by the nodes adjacent to the failing link, which configure their switches to loop back all the lightpaths that use the link, through the rest of the ring all the way to its other end, where they are switched to the remaining part of their route. This solution also handles channel failures. The overhead involved is:

* Switching: One additional port per switch is required.
* Hops: Each channel goes through at most three switches in a node. However, a looped-back lightpath goes through N additional nodes.
* Coordination: Since both ends of a link perform identical operations, no coordination is required.

A management scheme to ensure proper operation in case of multiple faults is proposed. This requires 50 percent of the channels to be reserved for backup purposes, which is the minimum for any scheme, and long loopback paths.

- **Schemes for node faults**

This is the severest fault and is handled by using coordination between nodes. Two solutions are proposed. One requires more hardware, and is a simple extension of the link fault handling scheme. The other solution is based on sophisticated connection patterns between the nodes, and requires no additional hardware. This second solution requires coordination between nodes, and therefore, is not suited to networks requiring fast restoration. Details of the algorithms are available in [7].

An integrated solution for handling all the above faults is also proposed in [7]. This scheme requires some coordination to diagnose the fault type. In this case, the nodes adjacent to a fault first *assume* that a link fault has occurred and activate the link recovery procedure. Then the node that is clockwise to one of the nodes considered above checks if there is another link failure. If not, then the previous assumption of link failure is true, else, it is a node failure. Appropriate action is then taken.

5 Simulation and Design Tools:

Software tools for effective simulation of failure scenarios is extremely essential for evaluation of different recovery schemes, study of different trade-offs and for the design of survivable networks.

5.1 Tools at the University of Ghent

A set of Design and Evaluation tools have been developed at the University of Ghent, Belgium[9] which are C++ based and have GUI-based and character-based executables. They run on Windows95/NT and Unix platforms. These tools are not available for commercial or general use yet, because there is no manual or technical support available. Therefore the descriptions given below are claims of the developers and have not been confirmed locally. However, it is not unreasonable to accept the claims as results using the following tools have been published. These include:

1. **Atena**: Analysis Tool to Evaluate the Network Availability
   This is useful for the comparison of network designs with respect to their reliability, pre-calculation of alternative route tables (using restoration strategies based on Dijkstra's shortest path algorithm, and minimum cost flow algorithms) and for the evaluation of single or multi-layer restoration strategies. The tool allows for "easy plugging in" of new restoration strategies.
2. **BONUS**:Broadband Network Survivability Simulator
   It is useful for engineering and evaluating novel distributed survivability strategies for broadband communication networks. It considers transmission and switching technologies such as ATM, SDH(SONET) and WDM. A simulation session using BONUS produces a detailed log of the execution of the distributed strategy. A plot of the recovery ratio[2]as a function of time, the number of generated recovery messages and the spare resource utilization.
3. **NetGen**:The Network Generator
   It generates sample networks quickly. It takes as input, the number of nodes, the positioning of nodes (random, regular etc), the connectivity matrix and the link capacity assignment. It is used to generate good starting solutions which can be used as input to planning tools with greater emphasis on cost minimization and the evaluation/comparison/sensitivity analysis of all kinds of network algorithms.
4. **SHARP**:SDH(SONET) Self Healing Ring Planner
   SHARP allows for the design of a new SONET infrastructure spread over several years, with minimum investment. It has different modules that basically assist the

[2]The recovery ratio is defined as the ratio of the number of recoveries (link,node or channel) from failure to the number of failures.

user in designing and verifying an SDH network topology. It is very well suited to be used as a network editor.

5. **WDMSim**: A simulation tool for multi-wavelength optical networks
   It is a tool to model and evaluate all-optical and mixed optical-electrical networks. It is aimed at developing design rules and to calculate network-performance metrics as blocking and network-availability to anticipate the impact of advanced system options. It is useful in topology planning (finding a minimal cost topology with specific survivability and traffic requirements, given constraints like hop count. It is also useful for optical layer routing and availability (survivability) calculations. This is done by generating a number of fiber or network element errors and investigating the amount of traffic which can be saved if protection or restoration is applied in one or more of the layers.

6. **IBCN Library**: C++ Components for network modeling
   This consists of a hierarchy of modules for reuse in different modeling problems,like network generation, statistical fault generation, modeling of multi-layer networks etc. It is extensible and not linked to any particular tool.

5.2 STRATEGIC OPTIONS

We have already mentioned STRATEGIC OPTIONS[14] in Chapter 2. This is a prototyping software to test and demonstrate methods for determining strategic locations and ring types for SONET ring placement in interoffice networks. Again, this is not a commercial package. This software chooses a set of SONET SHR's based on a cost comparison with 1:1/DP, which has been discussed in Section 2.2. The user inputs the nodes, links, connectivity, facility hierarchy (i.e. hubs and their clusters), topology costs and multiyear point-to-point demands of the network. The topology costs include fiber, route mileage, regenerator cost and regenerator threshold (maximum regenerator spacing). It consists of the Demand Bundler, Ring Selector, Topology Optimizer, Ring Router and Cost Multiplexer modules. This prototyping software was run[14] on a LATA network with 23 nodes and 36 links. A ten-year planning period was used. First, a pure dual-homed 1:1/DP architecture was designed and then a dual-homed SHR architecture was designed using STRATEGIC OPTIONS. The cost of the network with SHR's was observed to be 10% lower than the cost of the 1:1/DP network. The worst-case survivability for 1:1/DP with dual-homing was 23% as compared to 40% for the dual-homed SHR case. Thus survivability was seen to increase by 17% and cost was seen to go down by 10% when SHR's were used. Each network design took 15 minutes approximately.

5.3 TENDRA: A Tool to evaluate Distributed Network Algorithms

TENDRA is a tool developed at British Telecom [12] to evaluate distributed network algorithms. It can be applied to any network topology where data relating to the topology, elements and the Distributed Restoration Algorithm to be simulated are known, and may also include mean time to repair (MTTR), mean time between failure (MTBF), cost and bit rate. Four simulation modes are discussed:

1. All-spans mode: Each span fails in turn and invokes a Restoration algorithm to find alternative routes, and the time taken to find each replacement route for all failed links being recorded and displayed for each scan;
2. Interactive mode: Allows the user to select which element to fail;
3. Free-run mode: A discrete event availability simulation, through which elements are failed and repaired randomly in accordance with their MTBF and MTTR;
4. All-nodes mode: Similar to All-spans mode, except that each node in the network fails in turn.

TENDRA outputs include:

- time to restore individual links following a failure;
- restoration routes found by an algorithm in response to a failure;
- number of messages sent during a restoration event.

A simulation test on a hypothetical network comprising 30 nodes and 57 spans with a total of 332 working links was run[12] in the all-spans mode. The results indicate that the distributed span restoration in a SONET (SDH) network is feasible in approximately 1 second, thus offering the possibility of restoration within the call drop-out threshold, providing customers an uninterrupted service. A processing time of 5 ms and a cross-connection time of 20 ms were assumed. These simulation tests proved that Distributed Restoration Algorithms are fast[3]. Besides, no databases are required during restoration using Distributed Algorithms, and hence there is no problem ensuring stored information is up to date and correct.

5.4 Optical Path Design Tools

In addition to the above, effective Optical Path accommodation[4] design tools have also been developed for large scale network design[8]. These tools not only set up Optical Paths, but also determine the amount of network resources such as optical fibers and cross-connect system scale needed to accommodate Optical Paths.

[3] It has been claimed in [12] that sub-second restoration in an SDH network is possible using Distributed Restoration Algorithms as compared to minutes taken for centralized schemes.

[4] The path accommodation process involves the problem of assigning wavelengths to paths, and heuristically setting up optical paths within a feasible time

The basic requirements for OP accommodation design tools[8] are an effective design strategy, modeling of the network (network restoration schemes and WP routing schemes), reasonably quick calculation of the path routes, path wavelengths, required optical cross-connect scale, required number of fibers and wavelength utilization of the link, proper display of results etc. The wavelength assignment problem with and without restoration is discussed and the effectiveness of the developed tools are also discussed in [8]. Using the developed tools, several OP accommodation designs were simulated and the difference in inter-office fiber requirements between the WP and VWP schemes were observed. The tools were utilized effectively to determine the effectiveness of OP networks and to assess the effects of each parameter on network optimization.
Good design tools therefore form a very important part in development of new techniques for survivable network design and restoration.

6 SUMMARY and CONCLUSIONS

In this report, we have seen the importance of survivability in high-speed telecommunication networks. We have discussed a framework for network survivability on the basis of a survivability function. We have also proposed a general framework for network restoration, independent of the layer at which restoration is to be done.

We examined the structure of SONET signals and the different techniques available for network restoration at the SONET level. Next, we talked about the Asynchronous Transfer Mode (ATM) and its intrinsic features for survivability. We also discussed different survivable ATM network architectures and Fast Restoration of ATM networks based on ATM-VP. Next, we discussed the fast emerging field of Photonic networks which use Wavelength Division Multiplexing (WDM) and provide high bandwidth. We saw that Virtual Wavelength Paths are better than Wavelength Paths and also saw different Optical Path accommodation techniques. A recent proposal[7] for the design of fault tolerant WDM ring networks using limited wavelength conversion was also studied. Different fault recovery schemes were discussed and compared. Finally, simulation tools for network performance evaluation, design, measurement of network availability were mentioned. Proposed tools for Optical Path Accommodation were also discussed in brief.

After observing the results of the above discussion, we can conclude that WDM-based optical networks are the technology of the future and can help us realize the goal of B-ISDN. We can use existing ATM/SONET technology along with photonic networks and employ optical path restoration and self-healing mechanisms in order to realize an extremely high-speed, efficient and survivable network for the future. The open issues for future research include defining a definite framework based on the procedure presented in Section 1.2 ensure network survivability and restoration, definition of standards in the restoration strategies to be followed, investigation of inexpensive network design methods in order to achieve a satisfactory measure of survivability, by making redundancies as reasonable as possible. We also await the commercial release of the tools mentioned before so that the results claimed by the developers can be verified and the tools can be used effectively for the design of a High-speed, Highly-survivable network architecture at each level i.e the WDM, the SONET and the ATM levels. We would also be interested in utilizing the high bandwidth of the optical network and the advanced capabilities of ATM to achieve this goal.

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