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On Fault-Tolerance and Bandwidth Consumption Within Fiber-Optic Media Networks

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1. Introduction

Transmission of real-time video signals has long been a domain of copper-based video switchers with or without synchronization or equalization of analog or digital signals. With the beginning era of high definition signals and the associated limitation of maximum cable lengths the need for a change to fiber-optic equipment was essential. Intrafacility transport of video data carrying high definition signals can reach lengths up to kilometers. Using fiber-optic connections for such networks, a new set of reliability requirements arises. Optical fibers feature a lower physical reliability than copper lines. The latter also can be repaired more easily, mostly by the usage of soldering irons. The transformation from circuit-switched lines to packet-switched networks in an application field where the bandwidth of a connection might range over 6 magnitudes from kilobits per second to gigabits per second, thus almost reaching the capacity of the underlying physical link, also influences the planning of such networks.

The goal of this article is to gather the state of the art in two closely related research areas: fault-tolerance and capacity planning for optical media networks. Fault-tolerance can only be achieved by redundancy, i.e. additional capacity has to be provided. Vice versa, sensible capacity planning is only possible when the type of fault-tolerance mechanism applied is known.

Both areas also represent special requirements in optical media networks. Optical links exhibit failure characteristics different from electrical links. Fault-tolerance, i.e. the establishment of an alternate route in the presence of a fault, is time-critical in media networks that transport video and audio streams which have to meet real-time requirements. Capacity planning in media networks is complicated by the fact that the high bandwidth requirements of video connections only allow a few such connections to share a line, while there are other types of signals with much lower bandwidth consumption so that hundreds of those can share a line.

The remainder of this article is structured as follows. Section 2 presents the necessary technical information about optical networks and the media data they transport. Section 3 summarizes fault-tolerance concepts for optical media networks. Section 4 then reports on issues of bandwidth consumption and capacity planning in such networks. Finally, Section 5 summarizes the article.

2. Optical networks and transported data

2.1 Network characteristics

All-optical networks (AO) represent connection hardware where not only the transmission lines consist of optical fibers, but where also the switching elements are purely optical. AO networks differ fundamentally from Optical-Electrical-Optical (OEO) networks. The main difference is the active conversion part within OEO networks which converts optical signals into the electrical domain for switching and forwarding using standard protocols, and after data manipulation back into the optical domain. This process takes time and therefore generates a certain switch-intrinsical latency time. Switches with high bandwidth capability consume a lot of electrical power which has to be taken into account during the planning process in more extensive installations. The protocol chosen also limits the usable bandwidth in OEO networks, while AO networks can use 100 percent of the available fiber bandwidth, theoretically. Table 1 compares the main properties of AO and OEO networks.

All Optical	OEO
Protocol independent	Protocol dependent
No conversion delays	Technology immanent latency
Little power consumption	Power consumption rises by network size
Bandwidth as high as carrier allows	Protocol dependent bandwidth
Circuit switched (per color)	Circuit and packet switched

Table 1. Differences between AO and OEO switched networks.

2.2 Networks as graphs

From the perspective of routing, an optical network is a *directed graph* or digraph $G = (V, E)$, where the set of nodes V comprises all sources of signals such as cameras and microphones, all switches and routers, and all sinks of signals such as audio mixers and monitors. The set of arcs $E \subseteq V \times V$ represents the optical links that transport the data. Each link $e \in E$ will be assigned a capacity $c(e)$. A network is *symmetric* if for each edge $(u, w) \in E$, also $(w, u) \in E$ and $c(u, w) = c(w, u)$, i.e. that edges are bidirectional.

A sequence $v_0, v_1, \ldots, v_n$ where $(v_i, v_{i+1}) \in E$ for all i is called a *path* of length n. Typically we assume paths to be simple, i.e. the nodes v_i on the path are all different. A directed graph is *strongly connected* if there is a path from u to w for any pair of nodes $u, w \in V$. In a strongly connected digraph, let us denote the length of the shortest path from u to w by $sp(u, w)$. Then, we call

$$D = \max_{u,w \in V} sp(u, w)$$

the *diameter* of the graph.

A strongly connected digraph is called *doubly connected* if it is still connected after the removal of an edge, or a node with its adjacent edges. If we partition the nodes into two sets V_1 and V_2 of almost equal size, i.e. $-1 \leq |V_1| - |V_2| \leq 1$, then we call this a *bisection* and

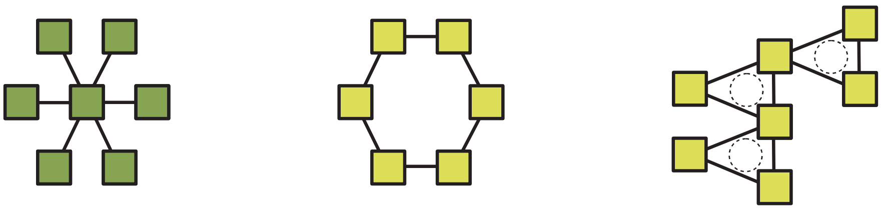
$$C(V_1, V_2) = \min \left\{ \sum_{u \in V_1, w \in V_2} c(u, w), \sum_{u \in V_1, w \in V_2} c(w, u) \right\}$$

is the capacity of the cut. The *bisection bandwidth* of a graph is the minimum capacity over all possible bisections.

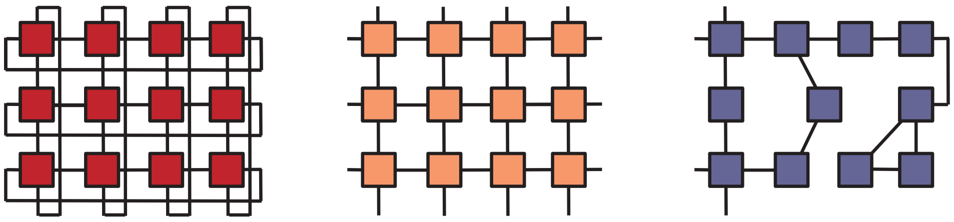
For a communication network, the connection property ensures reachability, while the doubly-connected property means reachability even in the presence of faults. The diameter bounds the number of hops, and the bisection bandwidth represents the total bandwidth available in a graph when there are many connections from sources to sinks.

Unfortunately, there is no single network that is doubly connected, has low diameter and a high bisection bandwidth, and is cost-efficient in the sense that the number of edges is still linear, i.e. that the average node degree is constant. Thus, a multitude of networks have been developed for different purposes, and with different properties.

A *star* is a symmetric network with node set $V = \{0, \ldots, n-1\}$ and edges $(0, i)$ for $i \geq 1$; node 0 is called the center. A *ring* is a symmetric network with $V = \{0, \ldots, n-1\}$ and edges $(i, i+1 \bmod n)$ for all i. A 2-dimensional *torus* is a symmetric network with node set $V = \{0, \ldots, n-1\}^2$ and edges $((i,j),(i+1 \bmod n, j))$ and $((i,j),(i,j+1 \bmod n))$. A 2-dimensional *grid* or *mesh* is similar to the torus, only the "wrap-around" edges between columns and rows 0 and $n-1$ are amiss. Examples of those networks are given in Figure 1.



Star Ring Ring of rings



(2D) Torus Grid (General) Mesh

Fig. 1. Examples of interconnection networks.

Large networks typically are constructed as a hierarchy of smaller networks, e.g. one might connect k stars of n nodes each by connecting the center nodes as a k-node ring. Also, networks evolving over time tend to develop some irregularity even if they started from some of the regular networks above. Thus, in a general mesh some edges of the grid can be amiss.

2.3 Media signals

By the term *media* within the broadcast branch we mainly mean audiovisual signals originally generated by microphones and video cameras. Those signals are converted in a way that they easily can be transmitted over electrical or optical networks. Auxiliary and control represent relatively small-bandwidth signals but they occur at a higher number than the media signals. They also can be routed along with the audiovisual signals. In the following we describe the relevant signals in more detail.

2.3.1 Audio signals

We mainly distinguish between *single stereo* audio channels bearing two mono channels *left* and *right* within one data stream and *multichannel* audio, where several audio channels, typically 8 or 64 mono-equivalent channels, are bonded together as one broadband stream. For all concurrently transported signals that originate from a single audio source, synchronicity between left and right channels in a stereo transmission and all up to eight channels within a multichannel transmission is very important. For audio-video connections also the so-called *lip-sync* synchronization exists that specifies a maximum limit of time shift between a video signal and the corresponding audio signals. Even a little time shift between both channels of a stereo signal would destroy the stereophony and the signal would not longer be useable. The audio standard AES3 (Audio Engineering Society) in IEC 60958 standard defines a copper or optical interface for a stereo signal representing two mono audio channels. The consumer version called Sony Philips Digital Interface (S/PDIF) also supports a fiber optic version. With 48 kHz and two channels on 24 bit resolution this results in a net bandwidth of around 2.3 Mbit/s. Packing AES3 frames into ATM cells is defined within standard AES47 (IEC 62365). This allows grouping of several single audio channels into streams of greater bandwidth. Alesis Digital Audio Tape (ADAT) in form of ADAT Lightpipe[1] is designed to carry 8 mono audio channels at 24 bits resulting in about 10 Mbit/s effective data rate. Besides ADAT there is the nowadays most popular Multichannel Audio Digital Interface (MADI) or AES10 interface, supporting up to 64 mono audio channels. MADI is available in two versions, a copper-based (per coax-cable) and an optical-based layout. The AES standard suggests a fixed bandwidth of about 100 Mbit/s.

2.3.2 Video signals

In the standard ITU-R BT 601 of the International Telecommunication Union the coding of digital video signals at *standard resolution* of 525 or 625 lines and 60 or 50 Hz respectively at 8 or 10 bit video resolution has been defined. Video aspect ratios (ratio of image width to height) of standard 4:3 and the newer one 16:9 are possible. The interfaces have been standardized in SMPTE 259M[2], where the effective data rate is specified at 270 Mbit/s.

High resolution video signals carry 720 or 1080 video lines at a great number of different image rates ranging from 24 to 60 Hz. The high definition serial digital interface (HD-SDI) is standardized within SMPTE Standard 292M carrying around 1.5 Gbit/s and within SMPTE 424M carrying around 3 Gbit/s. SMPTE 372M explains another, more rarely used dual link interface whose combined bandwidth also reaches about 3 Gbit/s. In both formats the integration of metadata was standardized. For both versions the integration of 16 synchronized mono audio signals plus adding of user bits for control purposes is provided. The high definition version is committed to a video aspect rate of 16:9 only.

Bandwidth consumptions using *video streams* concern more or less a fixed rate. Within SDTV signals a stream is represented at a data rate of around 50 Mbit/s. The same rate applies to HDTV signals, when the modern XDCAM-HD-4:2:2 (50) codec is used. Currently, besides the older GXF-versions (above 100 Mbit/s), within Central Europe this is the most utilized HDTV streaming format. Designed to be transferred over an old 100 Mbit/s Ethernet link this kind of video transmission perfectly fits into a hierarchy of fixed bandwidth channels.

Though this selection shows only an extract of the large number of different video formats, it covers the widely used ones.

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[1] As an alternative, ADAT optical interface, US-patent 5297181, can be used.

[2] Society of Motion Picture and Television Engineers, http://www.smpte.org

2.3.3 Control signals

Control signals in the broadcast environment differ in terms of their physical nature. They span from contacts which signal an ON-AIR condition with very little information content up to devices using control protocols for video mixers with a demand of a very short reaction time. Those signals have to be embedded efficiently within the available time slots considering bandwidth and latency.

2.3.4 Overview of bandwidth demand

Table 2 summarizes the different signals and their approximate net bandwidth. Note that there is only a very limited variety of signal bandwidth within the analyzed media signals. Video signals, especially high definition ones consume the majority of the available bandwidth. This fact can be utilized for an online routing heuristic for optimizing fault-tolerance, bandwidth and usage of fiber links (cf. Section 3).

Media bandwidth		
Signal type	Detail	Data rate [Mbit/s]
Video	SDTV	270 ($\sim$ 300)
	HDTV720p	1500
	HDTV1080p	3000
Audio	AES3	2.3 ($\sim$ 3)
	ADAT	10
	MADI	100
Control	RS-types	(upto) 1
Ethernet	100 Mbit/s	100
	1 Gbit/s	1000

Table 2. Overview of media bandwidth demand.

3. Network fault tolerance

Every fiber-optic based network is vulnerable to failures. Because of the huge number of signals a fiber can carry today, a single failure could cause an interruption of thousands of signals. To overcome this problem two main methodologies have been developed. The first is called *protection* which generally means use of redundancies in terms of additional links and physical replication and distribution of equipment in a mere static, predetermined manner, while the second approach *restoration* comprises diverse dynamic methods to recover from failures in very short time. Both approaches must guarantee that a failure of links does not lead to any perceptible or at least interfering interruption of services.

Both methodologies are suitable for solving most of the usually occurring problems. Decisions between them are made concerning a compromise between reliability and efficiency. While additional fiber-links and switches can be an important cost factor, restoration algorithms consume some time until bypass ways can be determined and switched, which could lead to unwanted short interruptions of services. Protection measures in general local-range ring topologies(Goralski, 2002) deal with delays that are composed of several parts. The signal speed in fibers is about 5 μs per kilometer (which can be ignored in local installations). The time for validation of protecting switching commands lies within 0.3 ms. Finally, the latency for bypassing a number of switches also has a significant influence in the protection time depending on the network topology. An ETSI demonstration ring listed in the APS specification 300 746 carrying only 16 nodes reaches an effective restoration time in the range of 20 seconds.

Fault tolerance methods in the computing domain like multiprocessing in Grids (Patrikar, 2009, pp. 531–546) differ from their pendants in the area of network resiliency and are not an issue of this chapter.

Protection in the area of networks means switching one or more source signals from a failed path to a working redundant backup path. When employing *1+1 protection*, there is a redundant path for every connection, and the signal is always sent over both paths to the destination. In the fault-free case, the receiver accepts the signal from one path based on the signal quality. In case of a link failure on one of the paths, the other path is still available. When employing *1:1 protection*, the redundant path is only used upon a failure on the original path. There are variants and generalizations of these basic scenarios. For example, low priority traffic can either be sent on the original or the redundant path. In *1:n protection*, n original paths share a redundant path at least partially. A compromise between 1:1 and 1:n protection is m:n protection, where $m < n$ redundant paths are available for n original paths.

These measures are also implemented within the RFC 3031 Multi Protocol Layer Switched Routing (MPLS) protocol. A functionality called *MPLS fast reroute* is implemented. In RFC 4090 an extension to the reservation protocol for Label Switched Paths (LSP) tunnels (RSVP-TE) is proposed. Backup tunnels are established, which work as bypass routes for one or several links. They are all computed in advance of a possible failure. Data traffic is redirected around a failed node or link as close as possible. There are two general protection methods used in MPLS. The *one-to-one-backup* method establishes an LSP that intersects the original path after the failed node, where after is to interpreted as downstream. For each protected LSP there will be a separate backup path. A *facility backup* creates a single LSP that serves several original LSPs. In MPLS language this path is called *bypass tunnel*. In most cases global recovery will require less bandwidth than local recovery. However, calculation of the optimal path in case of global recovery will need more resources and require more time.

3.1 Dynamic network restoration

To restrict the recovery time when engaging network management to calculate a restoration path, media networks mostly rely on heuristics. We will present several of them in the following paragraphs.

General network resilience methods for AO fiber networks are surveyed in (Wosinska et al., 2009). A fast distributed network restoration algorithm is presented in (Chow et al., 1993). In (Ramasubramanian & Chandak, 2008) the authors investigate how to cope with simultaneous failures on two links. They propose to refine the advance calculation of backup paths for point-to-point communications in the presence of single link failures. For every pair of links that may fail concurrently, the backup path for one of those links need not comprise the other (possibly failed) link. They formulate the problem with the help of linear programming and also provide a heuristic. In (Komine et al., 1990) the authors propose a distributed restoration algorithm for broadband networks. Instead of advance path reservation, they use a refined version of flooding to find alternate paths on the occurrence of failures. In (Yang & Hasegawa, 1988) the authors propose a distributed restoration algorithm for broadband networks that uses intelligent routers to restrict the number of messages when flooding in the case of failures. In (Zheng, 1992) the authors propose the use of backup channels for multiple point-to-point communications. Their focus is on guaranteeing real-time properties, notably bounds on end-to-end delay.

3.2 ZirkumFlex

ZirkumFlex (Messmer & Keller, 2010) is an example for a high-speed dynamic restoration heuristic. Therefore it does not rely on any pre-reserved path redundancy but calculates a failure bypass path around one or even several failed nodes or links immediately after failure signalling. If the restoration time, which consists of failure detection, failure signalling, signal detection, calculation of bypass routing, transmitting the routing commands, receiving and switching the signal paths on the router sites, can be held well below 80 ms, then only two video frames are lost and the signal interruption of the video signal is barely visible. Not only several node or link failures can be recovered in a very short time, also point-to-multipoint connections can be handled in addition to point-to-point connections. The tree structure of point-to-multipoint connections even contributes to reduce the time needed to calculate the bypass route.

The algorithm assumes the existence of sufficient bandwidth[3] available to support the bypass paths. Fail-stop as well as byzantine failures can be handled by this method. Failure handling works as following: After reception of failure information, which origins from information of lower protocols like loss-of-light information or CRC errors on signals, the (first) predecessor of the failed node(s) calculates the bypass path on its own topological information. After establishing the new path the links that are not needed anymore are removed by routing commands. The algorithm consists of three parts,

- Relaxation process
- Bypass breadth first search (BFS)
- Inverse link removal

which are briefly detailed now.

The *relaxation process* removes all links which can no longer be used, i.e. the links adjacent to a failed node or link and all further links which are reached only via nodes with indegree and outdegree 1. The predecessor and the successor nodes of the failed node, which represent the starting nodes for the next step (BFS) are moved as well. In case of the successor-BFS the removal process ends at a destination node or at a branch, a predecessor-BFS as well stops at a detected branch or a source node. The predecessor-BFS stops deleting links but still moves the BFS start node until a branch or source node is detected.

The *bypass BFS* run starts from the moved predecessor node and from the moved successor node(s) of the failed node in parallel. As long as new nodes are detected they get the current path information and their neighbors are visited. When the processes find an already visited node, both path representations are concatenated and automatically represent the bypass path between predecessor and/or successors. The corresponding successor BFS processes are stopped. If all successor BFS processes are stopped then also the predecessor BFS is stopped. A DFS run over the resulting bypass paths ensures that the bypass graph is loop-free.

In some cases the bypass routing leads to links in direction opposite to the former original path. The final *inverse link removal* adjusts in that situation. Knowing the distance to the source for each node, an opposite routing direction can easily be detected by decreasing distance information. If the bypass path would route a link from a node with larger distance to a node with smaller distance, this link would represent an unnecessary redundancy and has to be removed.

The resulting bypass path information then can be sent into the network to other routers and switches to establish the necessary connections.

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[3] In case of optic fiber a sufficient number of fiber links and/or colors is assumed.

4. Bandwidth consumption

Several models exist that consider the difference in bandwidth usage between the two paradigms AO and OEO networks. While pure AO networks route the signal only in the optical domain by means of optical switches and optical links which are still limited to single fibers and a relatively small set of laser colors as routing channels, more classical OEO networks operate in the electrical domain by switching paths, separating channels, shuffling signal streams in the electrical and subsequent optical stream and therefore handling datastream segments in more fine-grained amounts.

Considering both AO and OEO networks, media signals can be embedded into and removed from the network via so-called *add-drop multiplexers* (ADM). They generally integrate several different media streams into a single transport stream which is then sent via a fiber-optic interface to the neighboring switch(es). Figure 2 presents an example of several embedded signal streams in a 5 Gbit/s (5G) transport stream providing the available bandwidth.

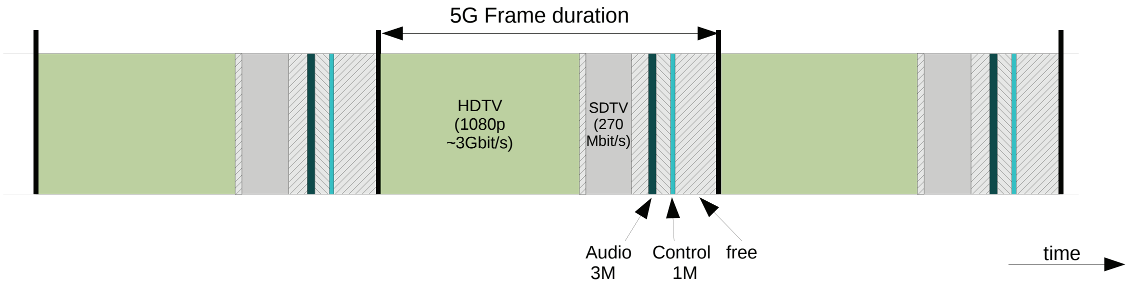

Fig. 2. Bandwidth allocation model for both OEO and AO networks.

Another network functionality within OEO network nodes is the capability to switch signals or groups of signals within the transport stream to other interfaces and to embed the media stream into other transport streams. This means removing (dropping) the media stream to a destination or leaving the media stream within the transport stream, copying and adding the stream to a new one known as multicasting or point-to-multipoint connections.

Concerning media switching there are some considerations to be made: One very important demand which has an impact to bandwidth calculations is the limitation of route-calculation time. Within medium-sized networks flow-based algorithms are too slow, so heuristics are to be chosen.

Load balancing as shown in (Chiu et al., 2002) also plays a minor role in media switching, see Section 4.2.1 for an example. To be considered is the huge bandwidth consumption of the HDTV-signal which e.g. in a 5 Gbit/s network consumes more than half of the available link bandwidth. This means that while switching a new link, the system should take care of keeping at least the bandwidth of one HDTV channel available. Demands with smaller bandwidth requirements should then be satisfied over different links if possible. We introduce a corresponding heuristic in Section 4.2.1.

4.1 Fault-tolerant interconnection methodologies and their bandwidth demand

Within fiber optic networks most of the failures will occur at the weakest points in the network: the optical fiber itself. Experience from practice indicates that *in-house* failures mostly concern single broken fibers, while *remote* line failures often occur during construction works, thereby the whole duct or even several ones concurrently are damaged. When designing a reliable fiber-optic media network this property has to be taken into account.

We now analyze the commonly known network topologies with respect to fault-tolerance and bandwidth consumption with exception of the *bus topology* which is not relevant for fiber optic networks. Layouts for chains, meshes, rings and trees are analyzed in (Gerstel & Zaks, 1994). Restore-management and the referring signal communication within OEO networks is extensively analyzed in the ETSI Automatic Protection Switching (APS) specification 300 746.

4.1.1 Star, double star, star-ring

A *star* topology allows simple adding of new nodes to the network. Failure of one terminal node does not affect the rest of the network. Also cable layouts can easily be modified. But the single star topology generally lacks redundancy and protection capability. A single point of failure is immanent: the central switch. Its failure would totally disrupt any communication on the network. This kind of network topology — combined with a strict redundancy of the central switch — still is very common within OEO media networks in practice. Besides it is the main choice for the emerging AO network topologies.

There are several ways to add fault-tolerance. An easy but expensive method called *double star* simply doubles the links from the central switch to the attached clients. One can choose between 1:1 or 1+1 protection, where at least for external connections like campus to campus one has to ensure that original and redundant links from one terminal to the center are placed in different ducts to really achieve redundancy. This doubles the necessary number of ducts. Using 1+1 protection, nearly transparent switching between failed and spare link is possible. Delays occur only by failure detection, signalling and backup switching which lie in the millisecond range, depending on technology. The disadvantage compared to 1:1 protection is that main path and spare path are busy and cannot be used for any other path reservation or transport of signals with lower priority.

Alternatively, the modification of a star by redesigning the network to a so-called *star-ring* brings a certain amount of redundancy and potential for protection measures. One or more Multiple Access Units represent the central switch base. Additional nodes can more easily be added by inserting additional central switches into the star-ring network without interruption of traffic. With this technique a bigger area than with star-only topology limited by its maximum fiber length can be covered. For this kind of networks some heuristic algorithms already exist. A distributed dynamic bandwidth allocation scheduling mechanism for star-ring protected networks is proposed in (Hwang et al., 2010).

4.1.2 Ring, double ring, multiring

For covering bigger network areas as with star topology as well as realizing backbone structures, *ring* topology efficiently can be used. The performance of the network is fair between all users. On the other hand, a single bidirectional ring can only deal with a single failure. Two failures disrupt all communication between the two isolated parts. Network reconfiguration, i.e. expanding or shrinking the system is problematic, because the ring has to be opened and several bypass and protection measures get obsolete during this step.

A well-known protection technology often used within multiplexing protocols for fiber-optic systems like Synchronous Digital Hierarchy (SDH) is the Multiplex Section-Shared Protection Ring (*MS-SPRing*) (Goralski, 2002). It exists in two variants, called 2-fiber MS-SPRing and 4-fiber MS-SPRing. The former version uses half of the available bandwidth for backup and/or lower priority communication. In case of a link failure this bandwidth is used to re-establish the ring communication. Lower prioritized communication can no longer be supported and is discarded. The latter version uses a double-ring topology with main and cold-spare rings. On failure of the main ring the protection system immediately switches from the main to the spare ring. Future installations as mentioned in (Reading, 2003) probably will make extensive use of the *Resilient Packet Ring* which is described in IEEE standard 802.17. It relies on the so-called self-healing capability of SONET/SDH networks. In contrary to protection measures like MS-SPRing this technology bases on packet-oriented connections which are used for Ethernet protocols for instance. It engages advanced bandwidth recycling mechanisms, a detailed discussion is out of scope.

4.1.3 Mesh and grid

A *mesh* is the most common form of network topologies within OEO networks. It can be tailored to the necessary number of network switches and/or links. Within a mesh or grid each network node is connected to at least one other node. A mesh network can be realized in a self-healing manner. This kind of network is appropriate to network recovery methods protection and restoration. The very common protection method p-cycle is analyzed by (Liu & Ruan, 2006) as well as by (Drid et al., 2009). Within meshes and grids path recovery methods are well surveyed. (Goralski, 2002) deals with the most common protection methods in general. Online restoration methods for example are presented in (Chow et al., 1993), (Komine et al., 1990) or in (Wosinska et al., 2009). The last reference presents software and hardware solutions for resiliency within all-optical networks. Another example for a high-speed algorithm for network-recovery called ZirkumFlex (Messmer & Keller, 2010) has been presented in Section 3.2.

4.2 Bandwidth-based classification of media streams

In Section 2.3 we described the most common media signals and their corresponding bandwidth. Remarkably there is a very limited variety of bandwidth. Grouping together signals with similar bandwidths results in Table 3. Because of the need to split the available bandwidth into discrete channels there is a certain lower limit for low-speed signals like contacts and signal lights (here expressed at 1 Mbit/s).

Description	BW [Mbit/s]	Group
Control lines	1	1
Stereo audio, communication channels	3	2
100 Mbit/s Ethernet, MADI, GXF HD Video	100	3
SDTV Video (audio incl.)	270	4
HD1080i Video (audio incl.)	1500	5
HD1080p Video (audio incl.)	3000	6

Table 3. Signals grouped by bandwidth.

We analyze three different scenarios concerning fiber-optic linking of media signals within broadcast stations. They differ in terms of reliability characteristics and physical realization. First we present the connection of a small studio or an in-house resource which is not intended to be highly transmission-substantial[4]. Though fault-tolerance is an issue, the connection is realized by several redundant fibers of only one single duct.
Second, for contrast, we discuss a local interconnection for a highly transmission-substantial area. In that case fault-tolerance is realized by way-disjoint ducts. The main cost factor is determined by the necessary number of routers and/or interfaces to be used.

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[4] A *transmission-substantial* facility must work properly in order to maintain the transmission signal path.

The third example represents the transmission-substantial connection from campus to campus. Such fiber links often are bought or rented by the single fiber, so the link itself is the cost factor to consider. This leads to a different kind of fault-tolerance and consequently to a difference in bandwidth usage.

4.2.1 Small studio interconnection

Figure 3 depicts a connection scheme between a small studio and a technical room as a general example of non-redundant wirings in terms of non-disjoint ducts within TV-studios. The majority of failures in this scenario happen by physical damage of single fibers while plugging, or on degradation of links because of dust or similar optical impairments, which in both cases lead to single-link failures.

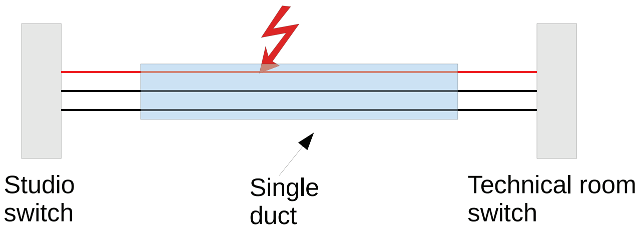

Fig. 3. Small studio interconnection.

We introduce a heuristic that represents an extended variant of the first-fit heuristic used to approximate the online bin-packing problem. To be considered are *fault-tolerance*, *optimal usage of fiber links* and *load balancing* in a special form that considers the huge differences in bandwidth between audio or control channels and HDTV-video links as shown in Table 3. Using a single duct, there is no reasonable protection method possible like in both other cases using disjoint ducts, so we had to find another scenario. We rely on a kind of load balancing for signals with bandwidth lower than HDTV in combination with the already mentioned ZirkumFlex algorithm for providing fault-tolerance for dynamic path restoration after network failure.

Our proposal guarantees that there will be bandwidth available for HDTV signals as long as possible. It conserves integral HDTV- or at least SDTV[5] bandwidths while paths of signals with small bandwidth can be switched one by one on a first-fit basis.

The proposed online algorithm takes a switch command as input, extracts the requested bandwidth information and checks for all available fibers sequentially if the available bandwidth is greater or equal than the requested one. Unless there is enough bandwidth available in fiber i, fiber $i+1$ is checked. If the last fiber has been reached and the requested bandwidth is not available, an error is returned. If the switch request can be served by fiber i there are three cases to be distinguished:

- There is enough available bandwidth to serve without reducing the number of HDTV and SDTV channels. Then the switch command immediately is executed on fiber i and the algorithm terminates.
- The number of available HDTV channels on fiber i must be reduced. We denote this condition by $\mathrm{HR}(i)$.

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[5] In this proposal we do not consider the formerly listed 1080i signal. The extension can be implemented in a straight forward way.

```
FOR i=1 to n DO
   if (bw <= cap(i) AND (!HR(i) AND !SR(i))  # no. of HD and SD
   then SWITCH(i), exit                      # channels remain
OD

FOR j=1 to n DO
   if (bw <= cap(j) AND !HR(j))              # no. of HD
   then SWITCH(j), exit                      # channels remain
OD

FOR k=1 to n DO
   if (bw <= cap(k))                         # else
   then SWITCH(k), exit                      # first fit strategy
OD

signal ERROR, exit
```

Fig. 4. Mapping of requests to fibers.

- The number of available SDTV channels must be reduced and the requested signal bandwidth is lower than SDTV. We denote this condition by SR(i).

If $cap(i)$ is the available bandwidth on link i, bw the bandwidth of the current request, and $bw(HDTV)$ the bandwidth consumed by one HDTV signal, i.e. 3000 Mbit/s, then condition HR(i) can be formulated as

$$\left\lfloor \frac{cap(i)}{bw(HDTV)} \right\rfloor - \left\lfloor \frac{cap(i) - bw}{bw(HDTV)} \right\rfloor > 0 \, .$$

Similarly, condition SR(i) can be formulated by substituting $bw(HDTV)$ with $bw(SDTV)$, i.e. 300 MBit/s.

The algorithm is formulated as pseudo-code in Figure 4. The runtime analysis shows that the three concatenated FOR statements question each of n fibers a constant number of times, giving $O(n)$ as runtime performance. This algorithm gives a high priority to HDTV signals which is substantial because typically the number of SDTV signals strongly outweighs the number of HDTV signals and so bandwidth for HDTV signals has to be conserved in the first place.

4.2.2 Intra-campus connection

Connections between broadcast-relevant facilities within a campus suffer of the same problems and failure types as already mentioned in the small studio case. The difference lies on the one hand in the kind of protection the links are equipped with, and on the other hand there are sufficient links available which can be combined in more than one duct.

In this scenario we suggest to consider a kind of signal priority. Figure 5 shows a two-duct combination. In-house connections usually suffer of single fiber failures as mentioned before. Highly transmission-substantial signals should be protected, i.e. for each signal-carrying fiber there should be provided one redundant fiber in the second duct giving a $1 + 1$ protection. Then a failure of several fibers up to one complete duct has no immediate visible (or audible) consequence. Lower prioritized signals can be restored by new calculation of paths or using the mentioned ZirkumFlex algorithm.

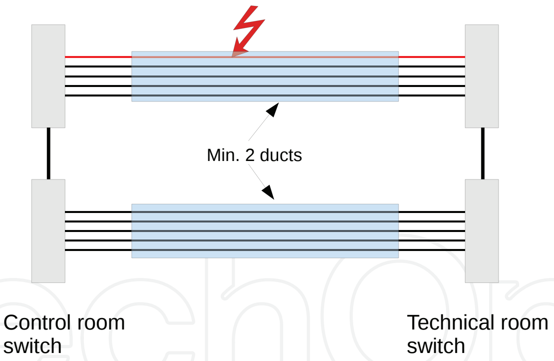

Fig. 5. Intra-campus connection.

4.2.3 Inter-campus connection

Remote studios must be connected via a multitude of links, mostly in dark fiber technology. It is important that the links are laid out geographically diverse, see Figure 6. Depending on the distance and purpose it may be favorable to rent links. In that case it is very important to use protection. CWDM or even DWDM technology is used to exploit the available fiber capacity. Therefore a failure of one link brings a total loss of the transferred signals and the protection link has to get active as quick as possible. This scenario is not suited for any known alternative to $1+1$ protection when transmission-substantial lines are in question.

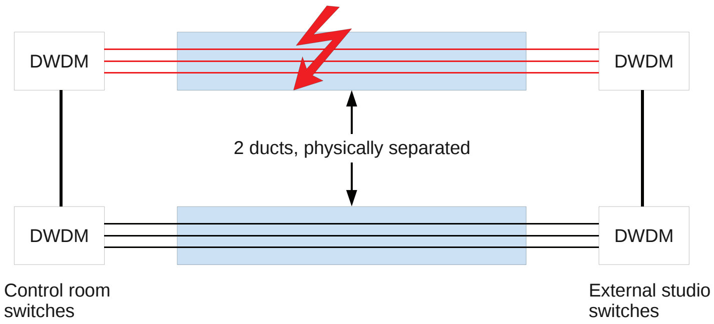

Fig. 6. Inter-campus connection.

5. Conclusion

We analyzed appropriate fault-tolerance concepts for high-speed optical broadcast networks and their influence on the bandwidth of currently used or planned networks of this kind. Besides mentioning the classic protection methodology and some heuristics for restoration methods we presented a novel approach for quick, dynamic restoration of network paths and introduced a heuristic for improved signal occupancy of fiber links in a high-definition video environment.

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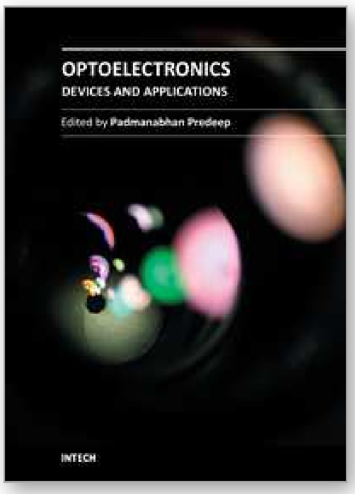

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