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**Cycle-Based Protection
for Optical Transport Networks**

Herausgegeben von

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1 Introduction and Motivation

Information society must be able to trust in a working network infrastructure for communication. As any real infrastructure, also communication network systems are subject to endogenous effects and exogenous influences. These effects and influences can intervene availability and operation of services provided for the network users. Since communication networks require precious resources for their realization and operation, it is one of the imperative challenges to find a compromise between resource efficiency and dependability of communication networks.

Networked information systems rely largely on optical fibers. Optical fiber is an exceptional medium, since it is not only able to provide long reach transmission, but it can also carry large information flows. In fact, the earth is wrapped into a mesh of millions of kilometers counting fibers, forming the backbone for interconnection of information systems. Wavelength division multiplexing is currently the key technique to make the fiber transmission capacities amenable, to cover the demand particularly required by data services as the Internet. It is the combination of a vulnerable medium as the fiber and its large transmission capacities which makes survivability of optical networks so important.

The importance is stressed further by the fact that outages occur frequently in networks. Network operators face fiber cuts occurring successively in the order of weeks or even days. While fiber cuts, mostly caused by backhoes during constructions, account for a significant part of outages, a plenty of other exogenous influences, like fires or earthquakes, and endogenous effects, like hardware faults and performance degradations, contribute to the vulnerability of optical network systems.

Because of the dependence of the users on the network, it is not sufficient to wait until a failure is repaired. For instance, localization and repair of a severed fiber can take hours to days, which is a critical disruption for many services using normally the fiber. This is the point at which the network itself is imposed responsibility to recover services until failures are repaired, which is the task of recovery mechanisms.

However, efficient utilization of resources, which is increasingly important for network operators under competition, dictates that simple overprovisioning by surrogate capacities in failure situations, as done by duplication of network entities, has to be avoided. It is understood that the network itself can provide more intelligent recovery mechanisms by reusing network capacities to achieve resource efficiency, while still guaranteeing a desired level of survivability. This benefit, however, comes at the price of higher operative and administrative complexity, and the amount of complexity is dependent on the type of recovery mechanism.

For many years, communication networks research has addressed survivability, particularly recovery mechanisms. Dedicated conferences [Dem98, Ebe00, CM01, Mac03] and

1 Introduction and Motivation

major research publications devoted to survivability [IEE90, Sch99, T1 01, Gro03a] underline not only its importance, but also the complexity and controversy of the topic.

Among the numerous approaches to recovery mechanisms, the concept of p -cycles [GS98a] appears on the horizon, fulfilling the predominant requirements under one umbrella. p -Cycle stands for *preconfigured protection cycle*, which already indicates beneficial features. Conceptually, p -cycles provide the merits of preconfiguration, i.e., fast and predictable recovery in conjunction with low nodal complexity, and the merits of cyclic structures, i.e., clear, simply manageable, and well-known network structures facilitating distributed recovery control. Because of resemblance to the accepted and established ring networks [EH88, ITU98b, Gro03a], p -cycles also ease migration into existing networks.

The capacity and survivability performance of p -cycles along with the applicability to optical networks, however, have necessitated further scrutiny. Fundamental questions naturally arise as: Are p -cycles more resource efficient than simple overprovisioning, and how efficient can p -cycles be at all? How do the characteristics of optical networks affect deployment of p -cycles? Are p -cycles capable to survive failure situations that are uncommon, but may still occur? It is the task of this thesis to answer these questions and to investigate the performance of p -cycles in optical networks.

Extensive comparative case studies, in this form firstly conducted within this work, allow us to evaluate the capacity performance of p -cycles. The survivability performance of p -cycles, along with consideration of importance gaining node failures and dual failures, is part of the research contributions on restorability and availability. In addition, the reader can expect novel insights into the p -cycle protection protocol, the issue of wavelength conversion in optical p -cycle networks, and the realization of dynamic p -cycle networks. Theoretical advances include results on redundancy bounds, the role Hamiltonian cycles, capacity smoothing effects, and the suggestion of “ p -paths.” The comprehensive summarization of research work on p -cycles can provide an overview particularly for those who are new to the topic.

The central research leitmotif is the aim to achieve efficient deployment of resources. This is typically expressed as efficient use of transmission capacity, since network cost correlates with installed capacity [Gro03a]. We define and regard the efficiency aim always within a context, in which additional requirements have to be met and other aims can coincide. We emphasize that resource efficiency not only means that investment cost can be spared, but also that less elements have to be operated, administered, and maintained.

The thesis is organized as follows. Chapter 2 lays the foundations for the following ones. Firstly, it gives an overview of optical transport network technology, abstracts to a network layer framework, and introduces basic definitions. Secondly, it outlines failure scenarios and survivability concepts, and treats the performance analysis of the latter. Chapter 3, also preparatory, aims at introducing p -cycles by elaborating on the concepts and the deployment alternatives for p -cycles. It is also the chapter which discusses related work on p -cycles.

Chapter 4 is devoted to the optimal design of p -cycle networks. It harmonizes and advances theory on optimal p -cycle design and presents methods to solve difficult p -cycle

design problems. Chapter 5 evaluates, in terms of resource requirements, the performance of p -cycles when deployed in transport networks. The evaluation directs at the influence of constraints inherent in optical networks and at the operation with dynamic traffic in emerging networks. Chapter 6 deals with the service-related performance of p -cycle networks. It suggests improvements for the p -cycle network design to survive failures beyond simple fiber failures and analyzes the service availability in p -cycle networks.

Chapter 7 comprises a conclusive summarization of the work and an outlook toward future research. Annex A formalizes the optimization models of this thesis. Annex B presents the networks for the case studies.

Each of Chapter 2 to 6 closes with a summary and a listing of the author's research contributions. Many contributions are also documented as articles in journals [SP04, SSG03b], as invited conference papers [Sch02c, Sch03a], as IEEE International Conference on Communications (ICC) publications [SS01, SGA02, Sch03b, SGC04], as International Workshop on Design of Reliable Communication Networks (DRCN) publications [Sch00, SAF01, SJH03, SSG03a], as contributions to other conferences [GS02, JHSS02, Sch02b, Sch02f, Sch02g, SK02, DCP⁺03, SP03, Sch04], and as book chapter contributions [Sch02d, Sch02e, CCD⁺03].