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p-Cycle protection at the glass fiber level

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ABSTRACT

The cost and complexity of wavelength assignment, wavelength conversion and wavelength-selective switching are always of primary considerations in the design of survivable optical networks. This proposal recognizes that as long as the loss budgets are adequate, entire DWDM wavebands could be restored with no switching or manipulation of individual lightpaths; so that the DWDM layer would never know the break happened. And environments where fiber switching devices are low cost, and ducts are full of dark fibers provide a very low cost alternative to protect an entire DWDM transport layer (or working capacity envelope) against the single largest cause of outage. Yet, while nodes and single DWDM channels may fail, a pre-dominant source of unavailability is the physical damage of optical cables. Thus, with the objectives of reducing the overall real CapEx costs and removing the complexity due to wavelength assignment and wavelength continuity constraints when configuring *p*-cycles in a fully transparent network context, this paper addresses the subsequent questions: if it is ultimately glass that fails, what if just the glass is directly replaced? More specifically, what if *p*-cycles were used to rapidly, simply and efficiently provide for the direct replacement of failed fiber sections with whole replacement fibers?

1. Introduction

After a dozen years of history, *p*-cycles are a now well-established and widely studied span-protecting architecture for network survivability. One of the main reasons why *p*-cycles have been gaining interest over the last decade is low capacity requirement in the designs, in comparison to that needed when using other network protection methods. Another interesting and attractive property of *p*-cycles is their inherent and efficient response to such advanced questions as single and dual span failure protection, node failure recovery, optical reach control, wavelength assignment and same wavelength protection [1–3]. But despite so many advantages, the practicability of *p*-cycles vis-à-vis that of path-protecting pre-cross-connected schemes has remained questionable from the capital expenditure (CapEx) cost perspective because of *wavelength switching* operations.

1.1. Background on wavelength switched p-cycles

In fact, *p*-cycle configuration types available within the literature typically assume a protection switching based on the wavelength granularity level. Accordingly, authors in [4] distinguish between three types of *p*-cycle configuration in the WDM layer: i.e., *opaque*, *hybrid* and *fully transparent* *p*-cycle designs. For each configuration type, the first lines in Fig. 1 illustrate pre-failure state paths; while the bottom lines *plus* the second and third nodes in the first lines, and their connecting links comprise *p*-cycles. The opaque configuration case (Fig. 1(a)) implies wavelength discontinuities and thus, o-e-o conversion at every node across working paths and along *p*-cycles. This means every working path and *p*-cycle leaves and re-enters the optical domain to access the next span on which it probably rides onto a different wavelength. In the hybrid configuration type (Fig. 1(b)), pre-failure paths and *p*-cycles are (independently) transparent; meaning that each of them uses the same wavelength from end-to-end. But a given *p*-cycle is not required to ride onto the same wavelength as the working paths it handles. For effective post-failure network states, wavelength conversion is partially required and located at the entry points of failed paths into *p*-cycles. In the fully transparent context (Fig. 1(c)), working paths and *p*-cycles are still transparent as with hybrids. But the (same) wavelength used by any given working path is now also required for its protecting cycles: post-failure states only assume an optical switching and the bypass of electrical switches. In contrast to opaque and hybrid wavelength switched *p*-cycles, an effective transparent *p*-cycle design subsequently requires the usage of two different types of fibers: one fiber set dedicated to normal state routing (only) and the other to protection channels.

Configuring *p*-cycles on a per-wavelength basis is generally more than attractive from the perspectives of flexibility in the

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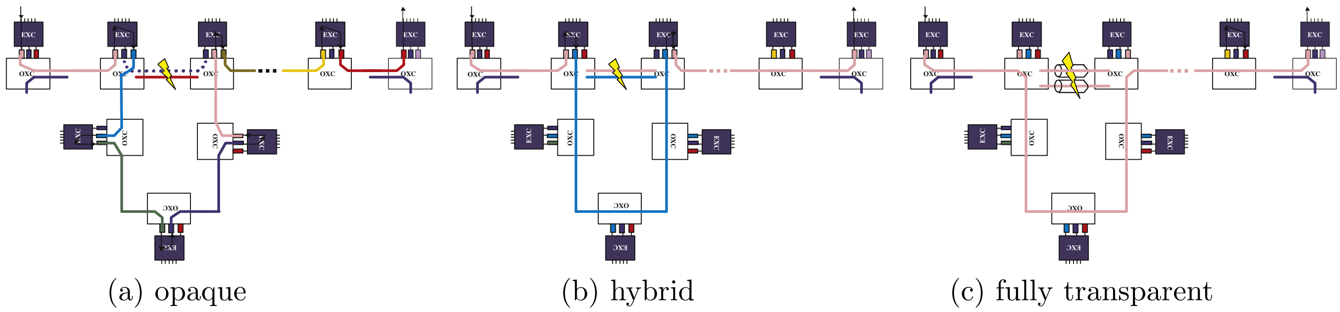

Fig. 1. *p*-Cycle configuration in the WDM layer (post-failure states).

routing of working paths and freedom in the selection of protecting structures. But in [5], we brought to attention that wavelength switching operations in the restored network state greatly increase equipment prices. Where wavelength conversion is allowed, either at *p*-cycle entry nodes or at every node crossed en route, high equipment costs are incurred because of optic-electronic-optical (o-e-o) conversion from one span to the next, or from the working path to the protection cycle and vice versa. In contrast, fully transparent designs eliminate the needs for electrical switching; nevertheless, much more fiber ports are required on the network nodes in order to accommodate working and protection fibers across the network because working paths and *p*-cycles no longer ride onto the same fibers. As will be shown later in the paper, fully transparent *p*-cycles also bring computational issues and much more complexity in the design because of wavelength assignment and wavelength continuity constraints. (Appendix provides ILP design formulations for each of the above variants of wavelength switched *p*-cycles.).

1.2. Whole fiber switched p-cycles: a simple and cost-effective alternative

Glass switched *p*-cycles constitute a promising alternative to wavelength switched *p*-cycles in a fully transparent context. The idea is to keep the flexible normal state routing of wavelength based configurations; but use in place of optical cross-connects (OXCs), other cross-connect devices having the ability to switch (at once) all wavelengths of an entire failed fiber optic into a *p*-cycle formed out of span fibers. In [5], such a fiber-level protection was proven to have a great potential for eliminating wavelength continuity constraint and computational complexity issues in fully transparent *p*-cycle designs. Furthermore, obtaining a CapEx cost-effective design using span-protecting *p*-cycles required to substitute wavelength for glass switched *p*-cycles, with the cost of ports on the hypothetical fiber switch estimated to be 10% of the cost of wavelength selective ports on a traditional OXC.

1.2.1. History and related work

From a chronological perspective, reference [2] was the first to state that *p*-cycle structures can be configured on a *waveband* (as opposed to *wavelength*) basis, with each waveband of wavelengths treated as a single unit. The specific case where whole fiber optics define wavebands is now referred to as *whole fiber (or simply, "glass") switched p-cycles*. The concept of glass switched *p*-cycles is exciting in that to protect against fiber failures or span cuts, wavelength assignment within the failed fibers is irrelevant as long as *p*-cycle fibers support the same waveband. This means despite the general recognition that requiring wavelength continuity greatly complicates the basic service routing problem, there are no further complications due to protection considerations if *p*-cycles are used at the fiber-switching level to protect fully transparent transport networks. Implicitly, every wavelength assignment actually retains continuity under protection rerouting because the corresponding wavelength is by definition free for use on the fiber dedicated for protection (if not already in use protecting another failure).

Although unintentional, authors in [6] generated the first whole fiber switched *p*-cycle designs while providing *p*-cycle network solutions for homogeneous networks, which comprise spans of exactly two fiber optics with identical number of wavelength channels. As a result, only Hamiltonian cycle structures were involved in the solutions. Even though an effective *p*-cycle network design can still be based on a single Hamiltonian, with the attraction of a quite easy calculation, the preliminary study in [7] previously demonstrated that designs involving many complementary cycle structures give rise to increased efficiency from spare capacity requirement perspectives.

If [2,6] opened possibilities for fiber-level protection with *p*-cycles, the seeds of idea remained unexplored for many years. Perhaps the main reason why whole fiber switched *p*-cycles had not been seriously challenged is a widespread idea that whole fiber switching operations are very slow. In the preliminary study in [8], we proposed an actual state-of-the-art whole fiber cross-connect switch technology. Actually, we reviewed several commercial examples of whole fiber cross-connect switches with the purpose of supporting the practical feasibility of glass switched *p*-cycles. Doing so, we ventured a comparison of whole fiber cross connect switches with OXCs from the perspective of costs incurred. Also in [8], we revised the basic *p*-cycle design problem in a way matching fiber-level protection paradigms. But rather than using only Hamiltonian cycle structures, as [6] did, all possible candidate cycles were now considered as eligible in the design.

1.2.2. Objectives and outline

The present paper is an extension of the proposal [8], which was presented one year ago at the conference on the *Design of Reliable Communication Networks* (DRCN'09). The aim of this new proposal is to provide glass switched *p*-cycles with supporting theory and additional experimental results from the technological, mathematical programming and CapEx cost perspectives. More specifically, this paper provides more background on wavelength switched *p*-cycles and discusses possible issues in order to justify the relevance of whole fiber switched *p*-cycles. Also in this contribution, we will study ILP mathematical formulations related to the design of wavelength and glass switched *p*-cycles; and the complexity reduction of glass switched *p*-cycle ILP vis-à-vis that of fully transparent *p*-cycle ILP model for several network instances. From the experimental viewpoint, a fully detailed CapEx cost model will now be provided for *p*-cycle configuration types in the WDM layer. And many additional case studies and results will be discussed, instead of only one as in [8]. Results' discussion will no longer limit to the overall CapEx cost but will now cover spare capacity