# TECHNOLOGIES AND APPROACHES FOR DIVERSITY IN FIBER LOOP NETWORKS

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## ABSTRACT

The widespread deployment of optical fiber in telecommunications networks and increasing traffic carried on individual fibers have raised concerns about the survivability of optical networks in the event of cable cuts or node failures. This paper discusses active and passive multiplexing technologies and alternative architectural approaches to diverse routing to increase the availability in fiber networks. The focus here is on ways of achieving diversity when fiber is deployed in the subscriber loop. We show that the availability for a 1:1 protected system can be improved significantly by deploying fiber with alternate paths and duplicate nodes. Using specific network examples, we compare installed first costs of the active and passive multiplexing alternatives for various loop-diversity approaches. The results indicate that requirements for diverse routing may have a large impact on the choice of technologies and approaches for fiber-loop networks. Specifically, a passive double-star architecture employing dense wavelength-division multiplexing (WDM) techniques has the lowest installed first cost for loop diversity for every model network studied.

## 1. INTRODUCTION

The widespread deployment of optical fiber in telecommunications networks and increasing traffic carried on individual fibers have raised concerns about the need for link and node redundancy in optical networks to reduce service interruptions in the event of cable cuts or node failures [1]. Route diversity in interoffice fiber networks has already received much attention [2]. The focus here is on approaches to diversity when fiber is deployed in the subscriber loop — the connection between the customer and the serving central office (CO). These approaches are motivated by practical considerations. For instance, banks and brokerage firms have a very high priority for network reliability. Even in the current narrowband environment, these businesses have dual 1:1 protection systems via the same path or alternate paths for many of their communications links. This provides 1-for-1 backup of the links, with automatic switch-over to a backup link when a link failure occurs. In a broadband environment, where a cable cut might eliminate multiple 155 Mb/s communications lines, these concerns would probably be even higher.

This paper is organized as follows. Section 2 describes alternative approaches to diverse routing for fiber-loop networks. The availabilities of fiber-loop network using alternatives approaches are also compared with the unprotected system. Section 3 describes the single-star architecture and double-star architectures based on active and passive multiplexing technologies for the alternative approaches. Section 4 uses specific network examples to compare installed first costs of the architectural alternatives for various loop-diversity approaches. Section 5 summarizes our findings.

## 2. ALTERNATIVE APPROACHES

This study assumes the deployment of single-mode fiber to the customer premises (CP) or close to the CP. For purposes of privacy and operational simplicity, only star topologies are considered — privacy is more difficult to ensure for alternative topologies such as ring and bus architectures. Each fiber is used for unidirectional transmission, thereby requiring the deployment of fibers in pairs to achieve duplex connections.

Consider an unprotected system as shown in Fig. 1(a). The system is inoperative if any one of the three network elements — terminal equipment (TE) at the CP and CO, subscriber loop (SL), and CO — has a failure. The availability of the unprotected system is

$$A_0 = A_{TE} A_{SL} A_{CO}$$

where $A_{TE}$, $A_{SL}$, and $A_{CO}$ are the availabilities for the terminal equipment, subscriber loop, and CO, respectively. The component availabilities are given by the formula

$$A_{TE} = MTTF_{TE} / (MTTF_{TE} + MTTR_{TE})$$

where MTTF and MTTR denote the time to failure and the mean time to repair, respectively, and the same formula applies to $A_{SL}$ and $A_{CO}$. The three alternative approaches to loop diversity are described as follows. All approaches assume 1:1 protection for terminal equipment — optical line terminating multiplexers (OLTMs) — at the CP.

### 2.1 Single Path

This alternative, shown in Fig. 1(b), is analogous to today's loop carrier systems and assumes that both working and protection fibers are carried in a single cable. The design provides protection against terminal-equipment failure at the CP and CO. However, the system is vulnerable to subscriber-loop or CO failures which can cause the working and protection fibers and terminal equipment at the CO inoperative at the same time. In the normal operating state, both working and protection terminal equipment at the CO and customer premises are fully operational. When one of the two units has a failure, the other unit automatically takes over and provides continuous operation. The system can be restored to the normal state if the failed unit is repaired and put back into operation. The system is completely inoperative only if both units fail, or any of the subscriber-loop and CO fails. The availability of the single-path approach is

$$A_1 = \left[1 - (1 - A_{TE})^2\right] A_{SL} A_{CO}$$



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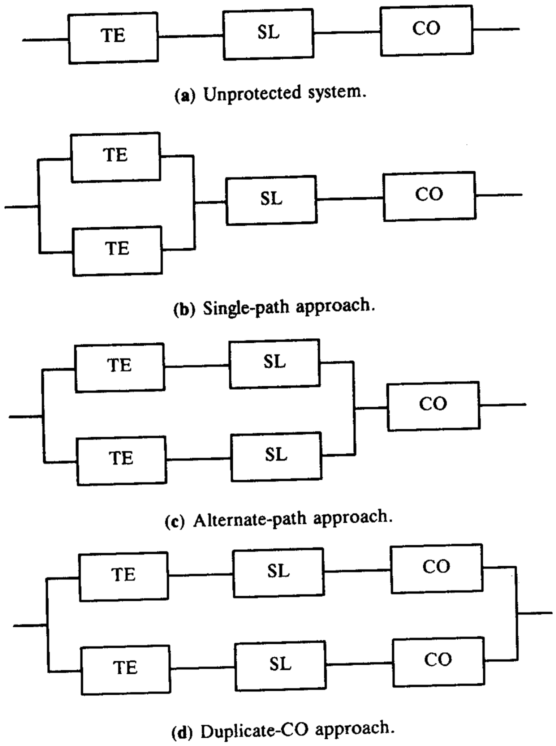


**Fig. 1.** Alternative approaches to the loop diversity.

## 2.2 Alternate Paths

This alternative, shown in Fig. 1(c), assumes that working and protection fibers follow physically separate paths to the same CO. This design provides protection against terminal-equipment and subscriber-loop failures. However, the system is still vulnerable to CO failures. The availability of the alternate-path approach is

$$A_2=\left[1-(1-A_{TE})^2\right]\left[1-(1-A_{SL})^2\right]A_{CO}$$

### 2.2.1 Duplicate COs

This alternative, illustrated in Fig. 1(d), assumes alternate paths are chosen to different COs. This design provides protection against terminal-equipment, subscriber-loop, and CO failures. The availability of the duplicate-CO approach is

$$A_3=\left[1-(1-A_{TE})^2\right]\left[1-(1-A_{SL})^2\right]\left[1-(1-A_{CO})^2\right]$$

Figure 2 compares the availability results based on the assumptions as shown. In general, $A_0 < A_1 < A_2 < A_3$. All availabilities increase as any MTTF increases or any MTTR decreases. More importantly, a very large increase in availabilities is realized with the alternate-path and duplicate-COs approaches. The remaining question is how to keep the incremental costs as small as possible for these loop-diversity approaches by using the double-star (or other) topology, as discussed in the following section.

## 3. ALTERNATIVE TECHNOLOGIES

For each of these approaches, we consider both single-star and double-star topologies. The single-star topology has dedicated fibers running from the CO to each CP. The double star has shared feeder fibers and dedicated distribution fibers which are joined at a remote node site as shown in Figs. 3–5. The darkened lines in Fig. 3 represent multiple distribution fibers connected to multiple 155 Mb/s OLTMs. Signals destined for different CPs are multiplexed together at the CO and are transmitted over the feeder fibers to the remote node, where they are demultiplexed and routed to the appropriate distribution fibers. Upstream transmission is similar, with signals from different CPs multiplexed together at the remote node and sent over the feeder to the CO, where they are demultiplexed and terminated at the switch. A principal motivation behind the double-star architecture is the potential cost savings through sharing of fibers in the outside plant, compared with the single star, which has fibers dedicated to each customer from the CO all the way to customer premises.

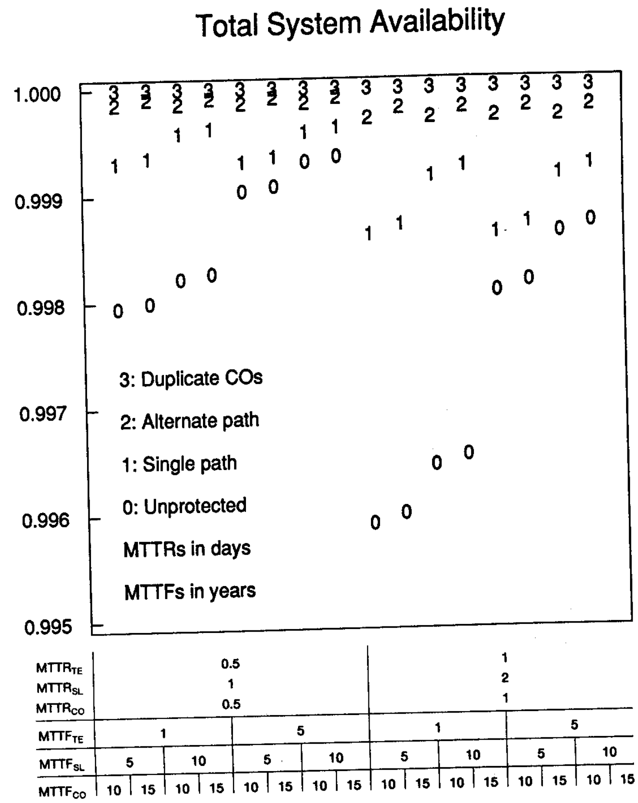


**Fig. 2.** Availabilities of alternative approaches.

Two alternative multiplexing technologies are considered for the broadband double star in Figs. 3–5. The first, an active double star (ADS) [3], utilizes high-speed (2.488 Gb/s) time-division multiplexing over the feeder, with electronics performing the demultiplexing and routing functions at the remote node. The space requirements and power dissipation of the broadband electronics might necessitate the use of a controlled environment vault (CEV) to house the remote node. The second, a passive double star known as the passive photonic loop (PPL) [4], uses multichannel WDM devices to perform the remote node demultiplexing and routing. The PPL represents a broad class of new network architectures that process

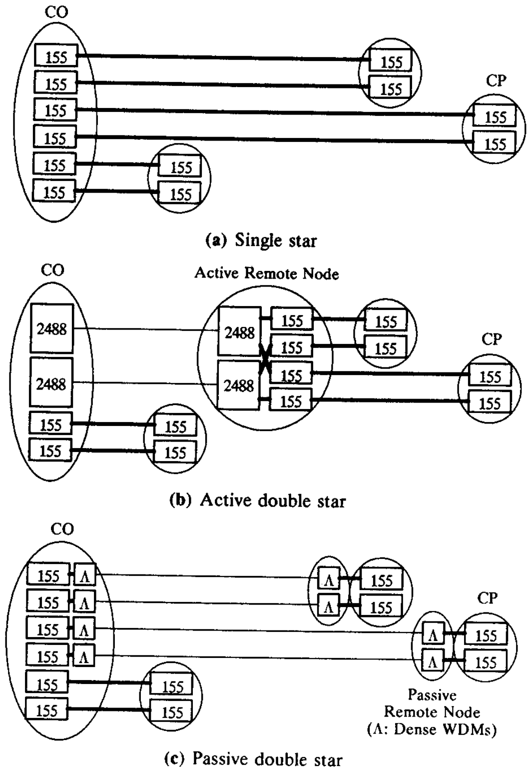


**Fig. 3.** Alternative architectures for single-path approach.

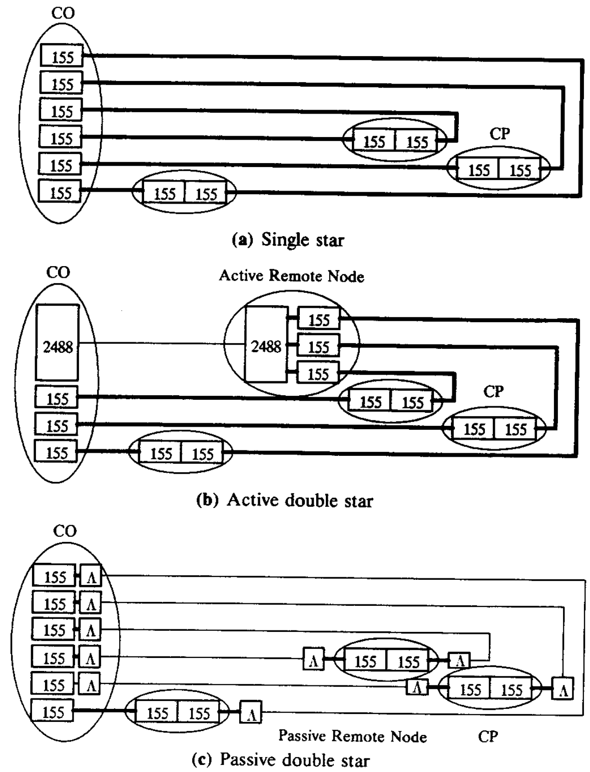


**Fig. 4.** Alternative architectures for alternate-path approach.

signals directly in the optical domain rather than via traditional, high-speed electronics. Since WDM devices are passive and compact, the passive remote node is much smaller than an active remote node; hence, it can be placed as close to the CP as possible to reduce the length of the distribution fibers. Other advantages of the PPL approach include the elimination of any CEVs (including remote power backup and back-to-back optical/electrical conversion at the remote node) and the likely reduction in remote maintenance requirements. This study assumes that the PPL architecture uses two separate 16-channel WDMs for upstream and downstream fibers with the remote node at the CP.

## 4. COST COMPARISONS

This section analyzes the installed first costs of the alternative loop architectures of Figs. 3 through 5. First, the single-path and alternate-path approaches are applied to a suburban network. The duplicate-COs approach is not considered because the cost can be prohibitively high for two distant COs. Second, the alternate-path and duplicate-COs approaches are applied to an urban network having two COs within a short distance. The cost of each network component is estimated by using a bottom-up method and learning curve projection [5,6]. For example, this study assumes a WDM-component cost of $50 per wavelength, a projection corresponding to volume production of 10,000 with 80% learning-curve slope and initial cost of $1,000 per wavelength.

### 4.1 Single Path vs. Alternate Paths

The network example shown in Fig. 6 has a CO currently serving 37 commercial/industrial and "high-tech" business locations through four feeder routes. The maximum length of these routes is 14,000 ft. Since only a small number (about 4% of the total) of residential lines are in feeder route 2, they are not considered in this study. Note that the triangle at feeder route 2 indicates a CEV equipped with loop carrier systems to serve telephone lines. It is assumed that the existing CEV and conduits are utilized. For the single-path approach, each fiber cable is tapered as fibers are dropped off at every location. For the alternate-path approach, however, the fiber cable does not taper because two routes (routes 1 and 2 or routes 3 and 4) can be connected by the dashed line (8,000 ft and 5,000 ft, respectively) shown in Fig. 6 as a ring. Each location has fibers routed to the CO through both clockwise and counterclockwise directions on the ring.

For this study, it is assumed that every location will require 12 drop fibers. Each fiber is used for unidirectional transmission at 155 Mb/s, so there are 6 pairs of drop fibers at every location. Both single-path and alternate-path loop architectures assume 1:1 protection for optical transceivers. That is, among the 6 pairs of fibers with optical transceivers for each customer, 3 pairs are working fibers and the other 3 are for protection. The working and protection fibers follow the same route or physically separate routes for the single path and the alternate paths scenarios, respectively.

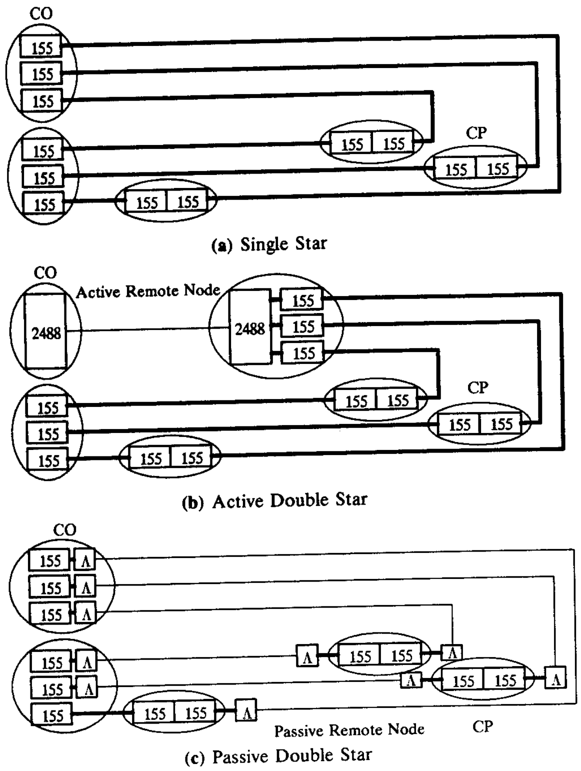


**Fig. 5.** Alternative architectures for duplicate-COs approach.

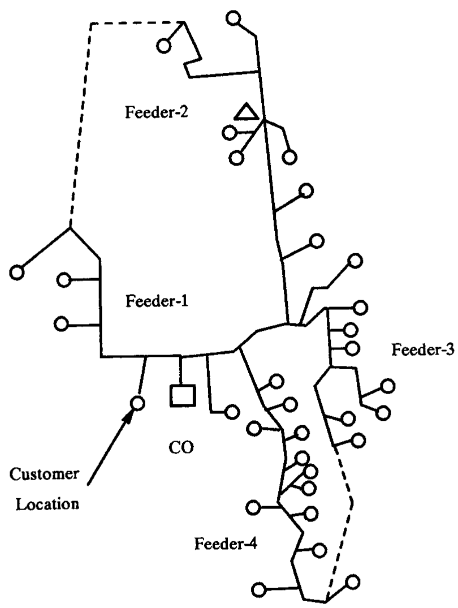


**Fig. 6.** Single-path and alternate-path approaches in a network.

Figure 7 shows installed first costs of the three architectures with 6 pairs of fibers for each CP for the single-path and alternate-path approaches. Both double-star architectures have lower fiber cable costs but higher optical transceiver costs compared to the single star because the ADS requires additional 16:1 multiplexers/demultiplexers and 2.4 Gb/s optical transceivers and because the PPL has costlier

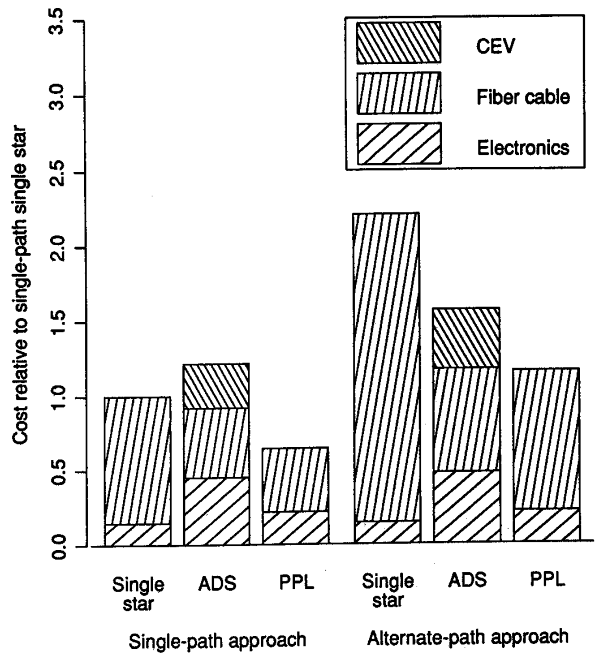


**Fig. 7.** Cost comparison for single-path and alternate-path approaches.

distributed feedback (DFB) lasers. For ADSs, the location of the remote node or CEV site for each feeder route is optimized to yield the lowest cost. Note that the optimal remote node site is insensitive to the number of fiber pairs per customer. For the single-path approach, the existing CEV at route 2 can be used because it is at the optimal site. This is, however, not the case for the alternate-path approach. Unlike the single-path results, the optimal remote node sites for the ADS are pushed farther away from the CO (even to the ends of routes 1, 2, and 4). This may suggest the use of a single remote node instead of two for the first ring (route 1 and 2). In terms of the single-path/single-star cost, the alternate-path/single-star cost is 221%, the ADS costs are 122% (single path) and 157% (alternate paths), and the PPL costs are 64% (single path) and 116% (alternate paths). The PPL with a single path has the lowest cost and the incremental cost for alternate paths is 80%.

## 4.2 Alternate Paths vs. Duplicate COs

The urban network example shown in Fig. 8 has different characteristics from the suburban area depicted in Fig. 6 — close proximity of two COs and high density of potential customers being the two most important differences. Both COs serve hundreds of office buildings housing major banking and brokerage firms. The area served is a 7,850 ft ring chosen based on 29 locations of existing buildings terminating fiber, and the other 29 locations assumed to terminate fiber in the future. In this area, the large population of potential broadband customers in a large number of office buildings suggests the use of multiplexing on the distribution fibers. Active multiplexing presents a number of problems. One problem is that the space assigned to operating telephone company equipment in office buildings is often inappropriate for the placement of powered electronics. The second problem is the

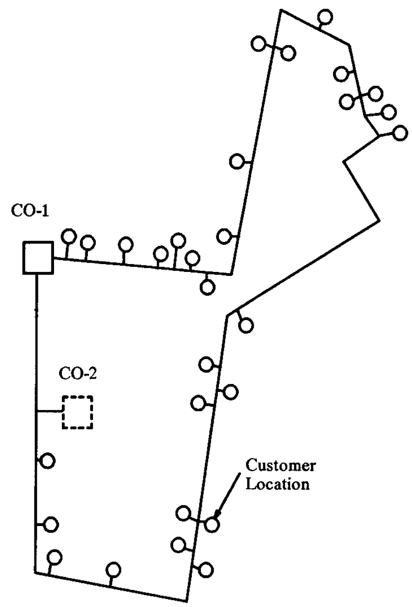


**Fig. 8.** Alternate-path and duplicate-COs approaches in a network.

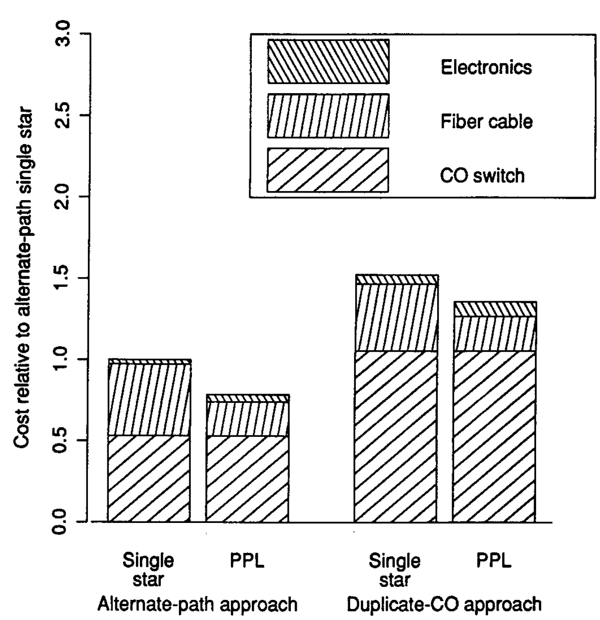


**Fig. 9.** Cost comparison for alternate-path and duplicate-COs approaches.

perceived security concern associated with multiplexing multiple customers at a common building location. Therefore, the approach considered here uses no active multiplexing. A PPL is assumed to provide a 16:1 fiber-gain ratio for 32 fibers (16 upstream and 16 downstream) at each building. With this approach a single fiber ring of 144 strands could provide duplicated fiber connectivity to 58 buildings, even allowing for an 80% fill factor. The first ring terminates at CO-1 as shown in Fig. 8. The second ring shown in Fig. 8 includes electronics at CO-2 and allows customers both fiber-cable and CO reliability at the cost of additional terminations on asynchronous transfer mode (ATM) switches. Although the total number of possible connections is greater, two 256-port ATM switches are assumed. That is, there is greater capacity in the loop than is available in switching at the CO, as is found today with narrowband switches in the CO and metallic pairs in the loop.

Figure 9 compares results for the single-star and PPL implementations of alternate-path and duplicate-COs approaches. The dominating cost component is the ATM switch. It should be noted that the PPL has lower fiber cable cost, the second major contributor to network costs. In terms of the alternate-path/single-star cost, the duplicate-COs/single-star cost is 153%, and the PPL costs are 78% (alternate paths) and 136% (duplicate COs). The PPL with alternate paths has the lowest cost and the incremental cost for duplicate COs is 75%.

## 5. CONCLUSIONS

This paper has analyzed active and passive multiplexing technologies and alternative architectural approaches to diverse routing for fiber-loop networks. The results indicate that requirements for diverse routing may have a large impact on choice of technologies and approaches. Significant increases in availabilities can be achieved by deploying fiber with alternate paths and homing on duplicate COs, respectively. In particular, the PPL alternatives have the lowest installed first costs for all loop-diversity approaches. The incremental cost of diversely routed paths in the loop network with PPL is 80% of the single-path cost for a suburban network. The cost increment in going from diversely routed paths to duplicate COs in an urban network is 75%. Therefore, a PPL architecture employing dense WDM techniques represents a very promising technological approach to cost-effective diverse routing in the loop.

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