IEEE Photonics Technology Letters, vol.19, no.5, pp.309-311, March 1, 2007, ©2007 IEEE

Network Agility Through Flexible Transponders

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***Abstract*— The emergence of on-demand and dynamic user services has led to a growing need for networks to be rapidly reconfigurable. To enable connections to be established without manual intervention, equipment such as transponders must be predeployed throughout the network, and the network must be flexible to configure this equipment as needed. One means of achieving network agility is through the deployment of advanced core optical switches. We discuss an alternative approach that uses flexible transponder and regenerator cards. The combination of flexible cards and relatively simple core switches can approach the full agility provided by more advanced switches.**

***Index Terms*—Agility, all-optical switch, configurability, OADM-MD, predeployment, regenerators, transponders**

I. INTRODUCTION

In current optical networks, most traffic connections are relatively static, with holding times on the order of months or longer. Provisioning new traffic typically takes weeks, with the equipment needed to support a new connection being manually deployed. However, with the emergence of applications such as grid computing, where a large data pipe is required for a short period of time, the network must be more agile to deliver bandwidth to where it is needed at a given time [1], [2]. Rapid connection setup, on the order of seconds or less, mandates that the process be automated and that all necessary equipment for the connection be predeployed.

Recent optical network advancements, such as all-optical network elements and long-reach optics, have significantly reduced the amount of equipment required to support an individual connection. However, transponders are still needed at the traffic endpoints, and depending on the length of the signal path, regeneration may be needed at a small number of intermediate sites. Thus, it is necessary to predeploy a number of transponders, and possibly regenerators, to be able to support dynamic traffic. (A transponder is a combination transmitter/receiver card that has a short reach interface on the client side and a WDM-compatible signal on the network side. Regeneration may be implemented through the use of back-to-back transponders or through lower-cost regenerator cards.)

Furthermore, the system should provide flexibility in how these transponders/regenerators are used so that a variety of network configurations can be supported with minimal capital investment. One approach to achieving this agility is to utilize flexible core switches; an overview of various switching architectures, based on all-optical network elements, is provided in the next section. An alternative approach is to employ flexible transponders and regenerators, which is the focus of this paper. Section III presents a novel transponder design that can achieve a high degree of edge flexibility thereby allowing deployed transponders to be used efficiently for dynamic traffic. The design scales such that it is suitable for arbitrary-degree nodes while maintaining low loss. Furthermore, as will be described, it is compatible with various protection schemes. The notion of flexible transponders is extended in Section IV to address regeneration. Overall, the architectures presented are a cost-effective means of addressing network reconfigurability.

II. MULTI-DEGREE OADMS AND ALL-OPTICAL SWITCHES

All-optical network elements allow a signal to remain in the optical domain as it traverses a node, rather than undergoing optical-electrical-optical (OEO) conversion at the node. In this section, we compare all-optical network elements for nodes of degree greater than two; however, the discussion applies to degree-two nodes as well. (The degree of a node refers to the number of physical links that are incident at the node.)

One such element is the multidegree optical add/drop multiplexer (OADM-MD) [3]; a functional illustration of a degree-3 OADM-MD is shown in Fig. 1(a). While the OADM-MD can add/drop or optically bypass any given wavelength, one important restriction is that the transponders on its add/drop ports are tied to a particular network port. Referring to the figure, note that transponder A can be used only to add/drop to/from network port 1. Thus, a client (e.g., an IP router) attached solely to this transponder would be forced to enter/leave the network through network port 1, which limits the network agility. To achieve greater flexibility, an adjunct edge switch would be needed to allow a client to connect to transponders on any of the network ports.

A more flexible network element is the all-optical switch, one architecture of which is functionally illustrated in Fig. 1(b). All-optical switches are typically architected using more scalable technology, thereby accommodating more switch ports [4]. This allows a subset of the ports to be used for local access, such that the add/drop traffic passes through the switch fabric. Transponders can thus access any of the network ports. Because of this greater flexibility, fewer transponders need to be predeployed at a node to meet the demands of dynamic traffic [5]. (All-optical switches of this type typically have at least five switch ports, as shown in Fig 1(b). While a

Manuscript received August 28, 2006; revised December 28, 2006.

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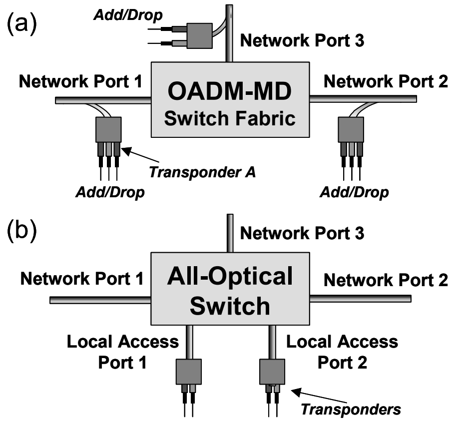

Fig. 1. (a) OADM-MD: each transponder is tied to a particular network port. (b) All-optical switch: transponders can access any of the network ports.

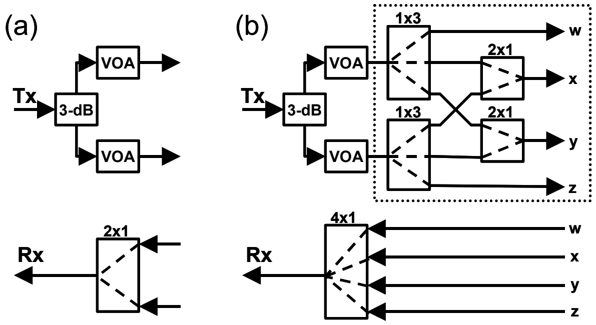

Fig. 2. A two-way (a) and a four-way (b) transponder, where the transmitter can access any one or any two ports to provide unprotected, 1+1, 1:1, or shared protected connections. The nominal loss in either design is 3-dB.

configuration with four switch ports is possible, i.e., three network ports and one local access port, this limits the nodal drop to 33%, or even less due to wavelength contention.)

The all-optical switch illustrated in Fig 1(b) can support additional services as well. In some implementations, it can allow the output of a single transponder to be multicast to multiple network ports (e.g., see [4]). It also can support cost-effective optical layer protection.

While the all-optical switch provides more flexibility, it requires a larger switch fabric and is thus a more complex and costly switch than the OADM-MD (although the cost increase may be offset by the reduced need for predeployed transponders or an adjunct switch). For technology and/or cost reasons, some networks have been deployed with OADM-MDs as opposed to all-optical switches. Thus, exploring alternative means of gaining agility that are compatible with the OADM-MD is important.

III. FLEXIBLE N-WAY TRANSPONDERS

Another option for achieving network edge agility is to deploy *flexible transponders* with an OADM-MD. Consider the two-way transponder shown in Fig. 2(a), where the transmitter output is split into two paths; each path feeds into a different add port on the OADM-MD. (It is desirable to use an optical backplane to connect the multiple feeds to their associated network ports to eliminate complex cabling.) Variable optical attenuators (VOAs) are used to control which of the two feeds passes through to a network fiber. On the receive side, a 2x1 switch selects one of the corresponding drop feeds. This transponder is then able to access either of two network ports, at the expense of approximately 3dB extra loss in the add path due to the splitter.

Note that this architecture is capable of multicasting over two network directions, and is capable of optical layer protection, where the work and protect paths are routed via the two network ports that the transponder can access.

While this design improves the transponder flexibility, it is not totally flexible if the nodal degree is greater than two. One option is to extend the architecture of Fig. 2(a) to an N-way transponder by splitting the add path into N feeds. However, as N increases, the increased optical loss would likely not be tolerable. (Even with a broadcast-and-select architecture, the extra loss is undesirable: e.g., maintaining the same system performance would require increasing either the transmitter laser power or the gain of the add-path broadband amp. The former could be expensive or not possible; the latter will result in greater ASE noise and power imbalance.)

An alternative architecture is proposed in Fig. 2(b). The four-way transponder shown in this figure is capable of accessing any of four network ports (labeled *w, x, y, z*). The circuitry contained in the dotted box of the figure forms a 'quasi' 2x4 switch, which is somewhat lower cost than a full 2x4. The nominal loss on the add path is on the order of 3dB. Furthermore, this architecture scales more generally to an N-way transponder, while maintaining a loss of approximately 3dB, through the use of: one 3-dB splitter, two VOAs, two 1x(N-1) switches and N-2 2x1 switches, along the add path. This architecture allows an edge device to access any of the N network ports by reconfiguring the transponder switches.

One property of this transponder architecture is that it can access no more than two network ports at one time (but note it can be *any* two ports). This is sufficient to support 1+1, 1:1 or shared-mesh optical-layer protection. In the case of 1+1, both VOAs pass the optical signal, and the transponder switches are set so that the desired work and protect paths are simultaneously accessed. In 1:1, only one of the VOAs passes the signal at any time; at the time of failure, the other VOA is activated. Fault-independent shared-mesh protection operates similarly to 1:1; at the time of failure, the other VOA is activated such that the shared backup path can be utilized (assuming it is free). The N-way transponder also supports shared restoration where the backup path is selected based on the fault location. This would require the transponder switches to be configured in reaction to the specific fault. While slower, it can be a more capacity efficient recovery mechanism.

Furthermore, consider a tertiary protection scheme where 1+1 optical layer protection is initially established. When a failure occurs to either of the two paths, the network establishes a new path so that there is 1+1 protection to protect against a second failure. For example, referring to Fig. 2(b), assume the initial 1+1 paths use network ports *w* (via the upper VOA) and *y* (via the lower VOA). If the path from port *y* fails, a new path can be established using ports *x* or *z* (via

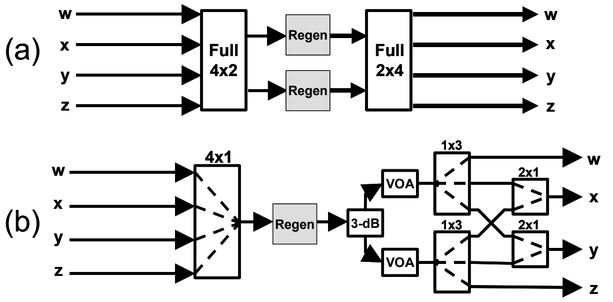

Fig. 3. (a) Degree-4 bi-directional regenerator that supports any bi-directional regeneration path. (b) Degree-4 unidirectional regenerator that supports any 1-to-2 multicasting.

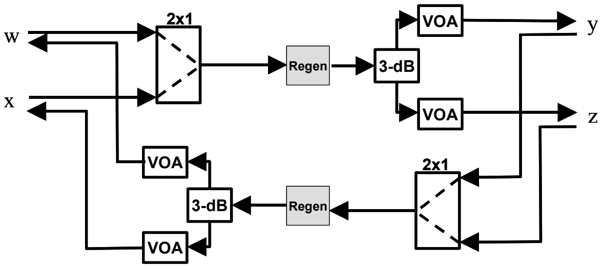

Fig. 4. Bi-directional regenerator that allows regeneration between ports w and y, w and z, x and y, or x and z.

the lower VOA), so that 1+1 protection is re-established. However, if the first failure occurs on the path from port *w*, and it is desired that the new path be established using port *z,* then this will require that the path already on port *y* be moved to the upper VOA. There will be a brief switchover during which the connection will be interrupted. This is a relatively minor limitation, however, it is possible to avoid switchovers by, for example, using a full 2x4 switch to replace the 'quasi' 2x4 shown in the dotted box of Fig. 2(b).

Because the N-way transponder can access all N network ports, the number of required predeployed transponders is the same as in the case of the all-optical switch. Overall, then, the combination of N-way transponders and OADM-MDs enables edge flexibility without requiring an adjunct edge switch, and achieves efficient use of predeployed cards without requiring the more expensive all-optical switch.

One limitation imposed by the ability to access only two network ports at once is that multicasting from a single transponder is limited to two directions; an all-optical switch can potentially multicast in all directions.

One possible limit on how large N can be is due to the number of transponders that can be supported by a single add/drop path because of splitting loss, number of possible connections in the chassis, etc. A single N-way transponder occupies N port connections, even though only one, or possibly two, are active at a given time. This suggests that only those transponders that are deployed for purposes of automatic reconfigurability should have the N-way capability.

Note that adding flexibility to the transponder will increase its failure rate somewhat. However, it allows for simpler core switches to be used, which have a lower failure rate.

IV. REGENERATION

The flexible transponder architecture described above can be extended to regenerator cards. The flexibility required at a regeneration site is the ability for a connection to enter and leave the regeneration node using any combination of two network ports. We focus on a degree-4 node, where there are 6 possible bi-directional regeneration paths through the node; however, the discussion extends to other nodal degrees.

Consider the regenerator card shown in Fig. 3(a). This card supports bi-directional connections, with no multicasting, and allows full regenerator flexibility across any combination of paths. Furthermore, it allows loopback, where a connection enters and leaves a node on the same port. Note that either the 4x2 switch or the 2x4 switch could be replaced by the simpler circuitry enclosed in the dotted box in Fig. 2(b).

In some scenarios it may be desirable to multicast the signal after it has been regenerated (e.g., to support tree-based routing). The regenerator card shown in Fig. 3(b) allows an incoming signal to be sent out on any combination of two ports. Note that this is a unidirectional regenerator card (multicast connections are typically unidirectional).

A simpler regenerator is shown in Fig. 4. Each side of this bi-directional regenerator is capable of accessing either of two network ports: ports *w* and *x* on one side, and ports *y* and *z* on the other. This allows regeneration to occur between links *w* and *y*, *w* and z, *x* and *y*, or *x* and *z*. With one card, four of the six possible regeneration paths are covered. To cover all six paths, two cards are needed. This would be more expensive than using a single regenerator card, as with Fig. 3(a), however, the design is less complex. Furthermore, in many practical networks, regeneration does not occur across all possible path combinations; only a subset of the regeneration paths may be required such that the architecture of Fig. 4 is sufficient. (The regenerator in Fig. 4 also is capable of unidirectional multicast; e.g., from port w to ports y and z.)

V. CONCLUSION

Rapid reconfigurability is a growing need in optical networks, requiring the predeployment of equipment such as transponders and regenerators. The ability to flexibly use this predeployed equipment is important for achieving a cost-effective network. One means of achieving this agility is through the use of flexible transponders and regenerators, as described in this paper. Using these flexible cards in combination with the OADM-MD offers almost as much edge agility as an all-optical switch.

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