Automatic Laser Shutdown Implications for All Optical Data Networks

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***Abstract*—Generalized multiprotocol label switching (GMPLS), optical packet, and burst-switched networks in which the synchronous digital hierarchy/synchronous optical network (SDH/SONET) layer is removed may be rendered nonfunctional because the current standard for triggering automatic power reduction (APR) cannot distinguish between a fiber that has been deenergized and a fiber failure. If this standard is applied, without modification, the likelihood of unnecessary amplifier shutdown in optical networks is significant. These shutdown events may impact large regions of the network and render optical links inoperable. To avoid unnecessary amplifier shutdown, amendments to the current operation of APR are suggested.**

***Index Terms*—Amplifier shutdown, automatic power reduction, generalized multiprotocol label switching (GMPLS), laser safety, optical burst switching, optical packet switching.**

I. Introduction

AT THE physical layer, today's optical core networks are based on static point-to-point transmission systems, which are interconnected via electrical add/drop multiplexers or cross-connects. In such networks, an optical path is set up manually as a synchronous digital hierarchy/synchronous optical network (SDH/SONET)-based circuit. Once set up, these "permanent connections" are continually energized with SDH/SONET frames being transferred whether or not any data is being relayed. Although this can be very wasteful of resources, especially when a link is carrying traffic that is only a fraction of the link capacity, it does have the benefit of enabling continuous management of the link. SDH/SONET is considered to be the leading technology for network management in optical networks.

One important aspect of SDH/SONET management is its ability to detect and recover from events such as fiber breaks and connector disconnects. Such events disrupt the continuous flow of optical energy in the fiber and so can be easily and rapidly detected with appropriately placed monitors. This enables alarms to be set-off to inform the Network Operations Center of the failure and automatic switching to stand-by circuits where provided.

An associated aspect of SDH/SONET management functionality is the implementation of automatic power reduction (APR) to protect workers and members of the public from exposure to hazardous levels of laser radiation. APR is based on the principle that a disruption of the continuous flow of optical energy most likely means that a fiber break or disconnect has occurred. Because this may result in a potentially hazardous exposure, the APR system rapidly reduces the optical power in the system to an intrinsically safe level.

SDH/SONET-based networks rely on higher layers to ensure efficient use of resources. In contrast, optimization of resource use is a key aspect of IP network paradigm [1]. IP networks are designed to maximize connectedness while minimizing the required resources.

For example, multiprotocol label switching (MPLS) uses protocols such as OSPF and IS-IS, which are based upon minimization of a metric associated with the traffic path. In such networks, paths are not permanent. Rather, they range from packet-switched paths, in which each packet is independently routed through the network, to label-switched paths (LSPs), which are generally short-lived (or "virtual") circuits.

In IP networks, paths that are suboptimal will carry reduced traffic, even to the extent of carrying no traffic at all. In packet transport networks, such as Ethernet LANs, there may be periods of time when no power is placed onto the link. Likewise, with technologies such as optical burst switching (OBS) or packet switching (OPS), there may also be periods of time when there is no power in a link.

Transporting IP packet traffic over SDH/SONET links is often criticized as very inefficient. Typically, several layers of protocols are deployed. The wavelength division multiplexing (WDM) layer provides physical connectivity, SDH/SONET provides management of the link, ATM can provide traffic management and reconfigurability, and IP provides service delivery to the customer. Recently, researchers have started to propose, design, and standardize new optical layer protocols to simplify this protocol stack [1], [2].

Such an approach has been proposed for optical networks with IP directly over WDM, which minimizes or removes the intervening layers. These proposals to simplify the protocol stack give rise to several network management issues. One such issue that has not been considered to date is the impact these new protocols will have on the functioning of APR in optical systems.

In this paper, we consider this issue and describe several potential problems that can arise by adopting the IP paradigm at the physical layer. It is shown that unnecessary amplifier shutdown in optical networks may be sufficiently frequent to degrade link performance. This is especially so in optical

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networks deploying next-generation switching technologies such as generalized multiprotocol label switching (GMPLS), OPS, and OBS. The likelihood of unnecessary amplifier shutdown is analytically quantified for a single link, as an example.

The impact of these unwanted amplifier shutdowns on network performance is also considered. These problems indicate that a reconsideration of several optical transmission systems standards is required.

Section II briefly discusses the new IP-based protocols that can result in unnecessary amplifier shutdown. Section III briefly discusses the need for laser safety practices and the current international Recommendation, ITU-T G.664, which specifies APR in optical systems. Section IV calculates the frequency of unnecessary amplifier shutdown that can occur in an IP optical network. Section V discusses the wider impact of these amplifier shutdown events in an all-optical network. Section VI proposes several solutions to these problems and the conclusions are presented in Section VII.

II. Next-Generation IP Optical Networks

GMPLS, OPS, and OBS have been developed for optical networks. All three stem from the idea of pushing the IP network paradigm down the protocol stack closer to the physical layer. In all three, the signal paths are set up when required and shutdown afterward. This allows reallocation of resources throughout the network, thereby improving resource utilization compared to circuit-switched SDH/SONET networks.

Currently, GMPLS uses LSPs to create short-lived "circuits" that are carried over a permanent SDH/SONET transport layer. More radical suggestions, such as GMPLS directly over WDM, OBS, and OPS, will result in the underlying optical transport layer being "turned off" or de-energized between connections, packets, or bursts [3]. We shall refer to such networks as "IP over optical networks." (By "de-energized," it is meant that the optical power carried by each wavelength within a fiber falls below the optical power associated with the transmit "zero" state.)

In a GMPLS network, optimization may result in links carrying asymmetric traffic. This will occur when the forward and return LSPs between two nodes follow two different physical paths through the network.

Although a network may be periodically reoptimized to reflect variations in the physical network, maintaining full or near-full utilization of all fibers over a long time scale is not an easy task. If the resource optimization protocols are left unfettered, it may result in some physical links carrying no traffic over an extended time period. Thus, we may find that some links are temporarily "turned off" until they are again required.

Today's medium and long-haul networks, being SDH/SONET based, have continuously energized fibers. Thus, the issues addressed in this paper do not occur in these "legacy" networks. However, OBS OPS-based networks that utilize short-term connections between end-users are being developed (see [4] and references therein). The issues discussed in the paper will have to be resolved for these types of networks to operate satisfactorily.

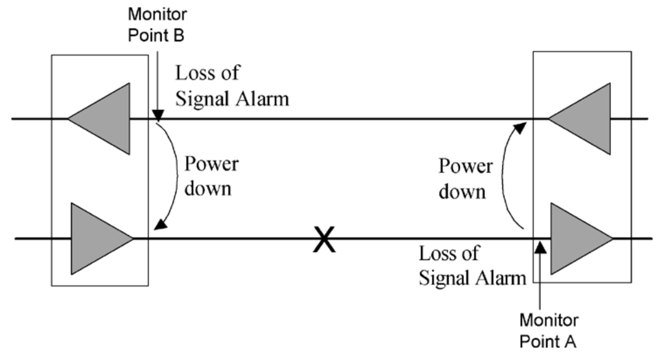

Fig. 1. Operation of APR as described in ITU-T G.664.

III. Laser Safety and Automatic Power Shutdown

The wavelength range used in modern optical systems is around 1550 nm—the near infrared. In this wavelength region, powers greater than 21.3 dBm emanating from a fiber end are considered to be intrinsically hazardous to the eye [5]. High power levels in optical communications systems are typically associated with the output of optical amplifiers such as erbium-doped fiber amplifiers (EDFAs) [6] or Raman fiber amplifiers [7].

Hazardous exposure of the human eye to an energized fiber is avoided through the use of APR, which effects rapid optical amplifier shutdown to an intrinsically safe output power. The method for triggering APR, described by the current ITU-T Recommendation G.664 [8], cannot distinguish between a fiber failure, including a fiber break or connector removal, and a de-energized fiber, which may result from a lull in the traffic.

The current ITU-T Recommendation G.664 assumes a transport layer, such as SDH/SONET, which provides a continuous flow of optical energy within a fiber. A consequence of this assumption is that the consequences of totally de-energizing an optical link, even for durations as short as 100 μs, can be quite drastic for large regions of the network.

The operation of APR prescribed by ITU-T Recommendation G.664 is depicted in Fig. 1. As shown in Fig. 1, when the lower fiber fails at point X, a loss of signal (LOS) event is detected at the next downstream monitor point A, which is located just before the amplifier (lower right), represented by a triangle. The LOS alarm is then raised and requires the amplifier (upper right) aligned in the opposite direction to shutdown, causing an LOS event to be detected at the downstream amplifier (upper left) for that direction (Monitor Point B). Upon the LOS alarm being raised at B, the amplifier upstream from the break (lower left) is shutdown, removing the hazard at the fiber break. This process results in a shutdown of all four amplifiers, thereby impacting traffic in both directions, in that link.

In case of a total cable break, both fibers simultaneously fail and the LOS events are detected at both monitor points and all four amplifiers are shutdown. Once all four amplifiers are shutdown, the fibers are de-energized and the cable break no longer poses a hazard.

An LOS alarm is detected at the monitor points if the optical power falls below a transmit "zero" state for more than 100 μs [9]. Once an LOS alarm is detected, the amplifiers must complete shutdown within 3 s [8]. The amplifiers cannot restart for

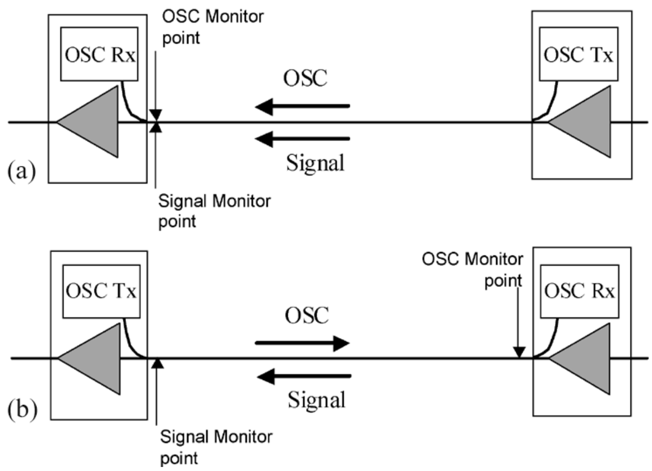

Fig. 2. (a) Copropagating OSC. The OSC is transmitted into the link to propagate in the same direction as the signal. (b) Counter-propagating OSC. The OSC is transmitted into the link to propagate in the opposite direction as the signal.

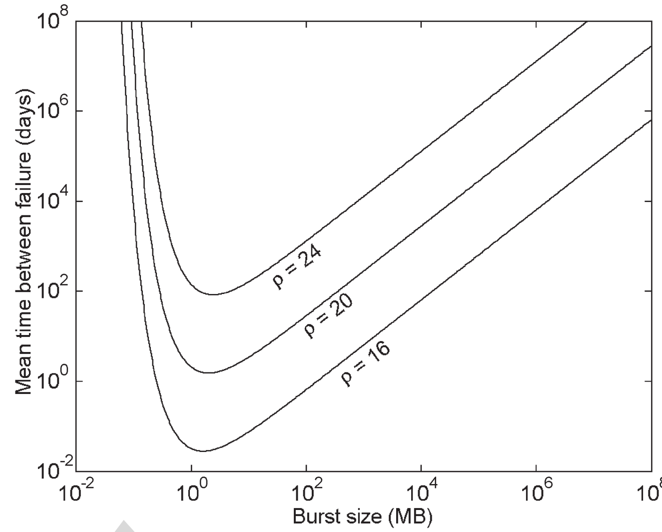

Fig. 3. Mean time between two successive unnecessary amplifier shutdowns T as a function of burst size for link offered load $\rho = 16, 20,$ and 24, $N = 100$ wavelengths.

a minimum of 100 s [8], beginning from the time they were shutdown. The restart typically involves sending "test" pulses down the link and checking that they are received at the far end. If not, the link failure is considered unresolved and a further 100-s delay is required before the next restart attempt. In some systems, if several automatic restarts fail, a manual restart will be required and an appropriate alarm is raised in the Network Management System.

Given this process, an LOS alarm will be triggered if every wavelength within a fiber is coincidentally free of traffic, that is, if the fiber is de-energized for a time period exceeding 100 μs. This will result in amplifier shutdown although the fiber is intact. We will refer to such an event as an "unnecessary amplifier shutdown." It is shown, in the next section, that the likelihood of unnecessary amplifier shutdown can be significant.

Some optical systems also deploy an "optical supervisory channel" (OSC), which is a separate low-power low-bit-rate channel used to monitor and manage the optical amplifiers in the link [8]. The OSC typically uses a wavelength that is away from the WDM channel band. The OSC is split out, detected, and processed at an amplifier site and then retransmitted on to the next amplifier site.

Although an OSC is not mandated by G.664, it does describe an option of using the OSC to test for fiber breaks. An OSC can be used to detect fiber failures and can copropagate or counter-propagate with respect to the signal, as depicted in Fig. 2. Not all deployed systems include an OSC, and some systems deploy an OSC only on a single fiber in a cable. We consider OSC in greater detail below.

IV. Probability of Unnecessary Amplifier Shutdown

Although unnecessary amplifier shutdown is likely to be more common in underutilized networks, depending on the distribution of traffic load, the problem may arise in highly utilized networks because GMPLS, OPS, and OBS generate a bursty traffic load. That is, sources make intermittent heavy demands on the optical link. Between these demands, the source is silent and the fiber is de-energized if there is no traffic demand for any of the wavelengths within the fiber.

To quantify the likelihood of unnecessary amplifier shutdown, consider an optical amplifier on a single fiber containing N wavelengths. Assume that packet, or burst, arrivals generated from sources incident to the fiber form a Poisson process with mean rate λ packets per time unit, and the mean packet transmission time is $1/\mu$ time units. Thus, the fiber has an offered load $\rho = \lambda/\mu$ and the mean time T between two successive unnecessary amplifier shutdowns can be approximated by

$$T = \frac{e^{\lambda\tau}}{\lambda} \sum_{n=0}^{N} \frac{\rho^n}{n!} \approx \frac{e^{\lambda\tau+\rho}}{\lambda}. \quad (1)$$

In (1) τ is the time that a fiber can remain in a de-energized state without triggering an LOS alarm at the monitor point. The derivation of (1) is given in the Appendix.

The approximation does not model the mandatory idle time that is required before an amplifier can be restarted following a shutdown and does not consider amplifier shutdowns resulting from fiber failures.

To show that the likelihood of unnecessary amplifier shutdown is significant, Fig. 3 plots the mean time T between two unnecessary amplifier shutdowns against the mean burst size for a constant offered load $\rho = 16, 20,$ and 24. (Since blocking is negligible, the offered load can be interpreted as approximately the average number of wavelengths carrying data at a given time.)

The mean burst size is the mean burst duration ρ/λ multiplied by the data rate of a single wavelength. Fig. 3 uses $N = 100$ wavelengths and a capacity of 10 Gb/s/wavelength with a shutdown time of $\tau = 100$ μs.

Note that very low link utilizations have been used. Shutdowns are most likely to occur during the quietest time of the day, and so the utilization during that time is the relevant measure.

Fig. 3 has two asymptotic regimes. For large burst sizes, lambda $\tau \ll \rho$ and T is directly proportional to the burst size and insensitive to τ. In this case, which corresponds to GMPLS, the time scale of the whole system is slow, giving long but widely spaced periods of shutdown. For small burst sizes, λ becomes large and T is dominated by the exponential in the numerator. In this case, which corresponds to OPS, there are very many short idle periods, but it is rare for an idle period to exceed τ. The worst performance is in the middle ground, corresponding to OBS time scales. Here, idle periods are relatively common, and yet a high proportion are longer than τ. Shutdowns are most frequent when $\lambda\tau = 1$.

It is worth noting that this shutdown rate is for a single fiber. In a large network, shutdowns can occur on any of hundreds or thousands of links, making the incidence of these events much more frequent.

In the next section, we will see that, in the case of a network, the problems arising from unnecessary amplifier shutdown are exacerbated for a variety of reasons.

V. Network Implications of Unnecessary Amplifier Shutdown

It might be argued that if a link shuts down only when it is idle, then unnecessary laser shutdowns will not cause problems. In this section, we show that active routes may also be shutdown if asymmetric routing is used. The immediate reduction in load may cause nearby links to shutdown and IP's reactive routing may make it difficult to restart the link. These will be discussed in turn.

As described above, an LOS alarm will power down the link in both directions. Although traffic in an SDH link is the same in both directions, this need not be the case in "IP over optical" networks. For example, the forward and return LSPs in a GMPLS network need not follow the same physical path [1], [2]. A similar situation can apply for OBS and OPS networks. This situation is depicted in Fig. 4, where the forward and return LSPs between routers A and B are shown as dashed arrows. Given the statistical nature of path utilization in an IP over optical network, it can occur that the optical power in one direction drops below the LOS failure level due to a lack of demand for LSPs from A to B. For example, in Fig. 4, assume that the optical power in a dashed path between OXCs 2 and 5 drops below the LOS failure level. This will cause an unnecessary amplifier shutdown in both directions on that link. In turn, all LSPs in the path D-2-5-C will drop out due to unnecessary amplifier shutdown. Hence, a reduction in demand between routers A and B may trigger LSP dropouts between routers C and D.

Further to this, with the link between OXCs 2 and 5 shutting down, the number of LSPs propagating out of OXCs 2 and 5 will be reduced. This reduction in traffic will increase the chances of other adjacent links also suffering false LOS alarms, and so the link shutdowns may cascade throughout regions of the network.

As stated above, once APR has been engaged, a 100-s delay is required before a restart can commence. In an SDH network, due to the permanent nature of the connections, there is traffic

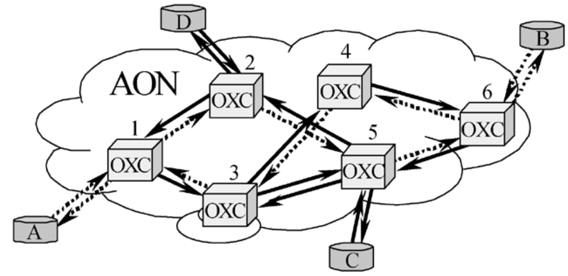

Fig. 4. IP over optical network consisting of optical cross connects (OXC) in the core that provide optical connections between access routers.

(i.e., SDH/SONET frames) ready to use the link once the restart is successful.

In contrast, with an IP over optical network, during the 100-s delay, the higher (IP) layer will reroute the dropped LSPs to alternate paths that avoid the 2–5 link. This raises a further problem in that, even after the restart attempt, there may be no traffic routed through the 2–5 link due to IP rerouting around the shutdown link. The lack of ready traffic will then result in subsequent LOS alarms in that link. This process may result in the link becoming permanently unavailable.

Therefore, it can be seen that the bidirectional nature of the current APR process may result in a lull in traffic in one direction in a single link, causing significant network performance degradation over a large region.

VI. Resolving the Issue of Unnecessary Amplifier Shutdown

This section describes several possible approaches to addressing the problem of unnecessary amplifier shutdown. In attempting to resolve this issue, we are not at liberty to relax the exposure times and optical powers as these are set by the safety considerations derived from IEC 60825 laser standard series, which is based upon known laser injury thresholds. Instead, we must consider applying engineering rules or protocols to the issue.

One approach is to use the network control plane to inform the monitor points when to expect a false LOS condition. The control plane is a separate network with the function of controlling the optical network elements (optical cross connects, etc.) to ensure the data traffic reaches its intended destination. Currently, there is a significant international effort being directed at developing a range of technologies and protocols for the optical network control plane [1], [2]. Given the size and complexity of transnational optical networks, the control plane will most certainly be based on a very large and sophisticated software program with interfaces to many network elements. With this approach, an extra functionality will have to be integrated into the control plane protocols to facilitate its interaction with the monitor points.

The distance covered by some optical networks can be some thousands of kilometers with many tens of optical amplifiers in a single link. If the control plane is to be used to "warn" the amplifier monitor points of an expected de-energizing of the link, then this message will have to be flooded along the entire length of the signal's intended optical path. Further, the messages must be timed to ensure the warnings correspond with the de-energized periods. This may be a rather challenging task.

An important issue with this approach is that the APR will become intimately entwined with the control plane protocols. Given the importance of APR in protecting workers and the public from hazardous laser exposure, the reliability of APR is of great significance. This is reflected by the fact that a significant portion of G.664 is allocated to calculating APR reliability [8]. Integrating the APR with the control plane will place an even stronger requirement on the control plane reliability and may make calculating the APR reliability somewhat more difficult.

A second approach would be to allow the link to shutdown and redesign the restart process (as described in G.664) to avoid the link from becoming unavailable or propagating the shutdown to other links. In this case, the restart procedure would have to be modified to provide energy to the monitor point before the IP layer reconfigured the network. This may require a reduction in the 100-s delay before restart attempts. Also, once the downstream monitor point received the restart pulses, the link would have to stay energized until traffic becomes available for the link. This would again require an interface between the laser safety protocol (G.664) and the IP routing protocols or control plane. Further, any redesign of the restart process must include safety principles; hence, this approach may not provide an acceptable laser safety regime.

A more practical approach may be to mandate the use the OSC. The OSC is a separate wavelength within each fiber used to monitor and control amplifiers and is typically a low-power low-data-rate channel outside the WDM wavelength band. Although the ITU-T G.664 standard does not mandate the use of an OSC to monitor for fiber breaks, it does suggest the use of an OSC to provide low optical power, and hence a safe method to check continuity of a link before full power is reapplied to a repaired link. The use of a low-power continuity check is particularly important in systems deploying high-power Raman amplification [7].

If a copropagating OSC is deployed [see Fig. 2(a)], a fiber failure is then considered to have occurred when the combined OSC and signal power level falls below the LOS threshold. Although the addition of an OSC appears to be a viable solution to the problem of avoiding unnecessary amplifier shutdown, it introduces a single point of failure at each fiber. The single point of failure manifests if the OSC laser fails when the fiber is de-energized for a sufficient time to trigger an LOS alarm.

Allocating more than one OSC in each fiber is a means to avoid a single point of failure. In the case that m OSCs are allocated, the LOS alarm is triggered if and only if the optical power carried by all m OSCs and the remaining wavelengths falls below the optical power associated with a transmit zero state for a sufficient time.

Consider again the model of an isolated fiber presented in Section IV. Suppose now that the fiber contains a total of $m + N$ wavelengths, where m of the wavelengths are allocated to OSCs and the remaining N are dense WDM (DWDM) channels. Assume that the mean time between failures of an OSC laser is exponentially distributed with mean lifetime $1/\eta$, the repair time of the laser is fixed at r and laser failures are statistically independent. The probability that all m OSC lasers are simultaneously under repair at an arbitrary time instant is given by $(\eta r/(1+r))^m$. By assuming that failure of an OSC laser is statistically independent of the fiber being in a de-energized state, it follows that the mean time T between the start and end of two de-energized periods, lasting for more than τ, and in which all m OSC lasers are simultaneously under repair can be approximated by

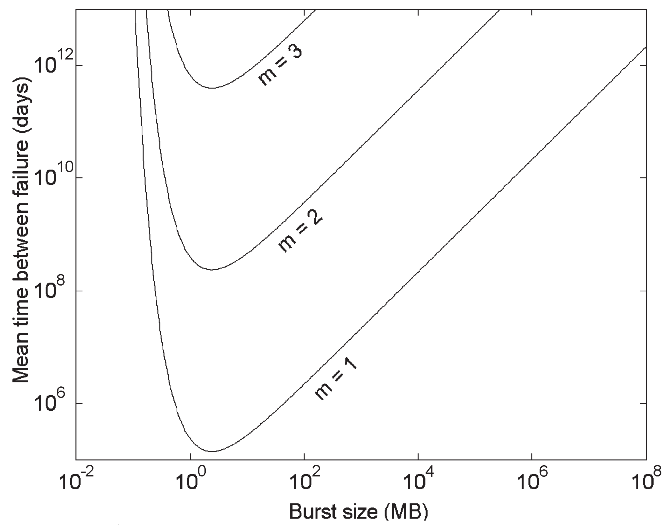

Fig. 5. Mean time between successive unnecessary amplifier shutdowns as a function of burst size, given $m = 1, 2, 3$ OSCs are allocated, $N = 100$ wavelengths, offered load $\rho = 20$, $1/\eta = 10$ years, and $r = 2$ days.

$$T \approx \left(1 + \frac{1}{\eta r}\right)^m \frac{e^{\lambda \tau}}{\lambda} \sum_{n=0}^{N} \frac{\rho^n}{n!}. \tag{2}$$

This equation is derived analogously to (1), but noting that the probability of an idle time that will cause a shutdown is no longer $e^{-\lambda r}$ (the probability that the fiber is de-energized for longer than duration τ), but now is $e^{-\lambda r}((\eta r)/(1+\eta r))^m$ (the probability that the fiber is de-energized longer than duration τ and that all m OSCs are under repair). To show that the likelihood of unnecessary amplifier shutdown is drastically reduced with the adoption of $m = 1, 2, 3$ OSCs, the mean time T between two successive unnecessary amplifier shutdowns is plotted against burst size in Fig. 5, where $N = 100$, for offered load $\rho = 20$. It is assumed that the mean time between failure of the OSC laser is $1/\eta = 10$ years (typical for modern DFB lasers) and the repair time of the laser is $r = 2$ days.

Comparing Figs. 3 and 5, we see that for a burst size of 1 MB, the mean time between unnecessary amplifier shutdowns is increased from about 1 day to more than 200 years with the addition of just one OSC.

A more cost-efficient approach would be to replace the m OSCs with one OSC and $m - 1$ SDH channels. In this approach, $m - 1$ of the additional channels will be revenue providing channels and not just overhead. With the continuous energizing of the SDH channels, these $m - 1$ channels will remove the single point of failure and still fulfill the role of the extra $m - 1$ OSCs.

If the network is based upon the automatically switched optical network (ASON) architecture [10], another option is to allocate the network-signaling channel to a separate WDM channel within the fiber. This "associated signaling" means the channel used to control the OXCs propagates through the same fiber as the data channel [11]. Although it is expected that the signaling channel protocol will be IP, by transporting it over a protocol such as SDH/SONET the fiber will be permanently energized, thus fulfilling the role of an extra OSC while carrying out a required network function. Yet another variant of this approach is to employ a "keep alive" signal on a separate WDM channel. Such a signal could provide some network signaling and management services as well as confirming the integrity of the physical path between nodes.

One disadvantage of a copropagating OSC is that, should a false LOS occur due to an OSC failure, the APR as described in the current version of G.664 will shutdown the link in both directions. This will cause the reverse path LSPs to drop out, as described in Section IV above, although the physical integrity of the link is still intact. This, in turn, may lead on to the cascaded shutdown scenario described in Section V.

Using a counter-propagating OSC [Fig. 2(b)], a fiber failure is considered to have occurred when the OSC power falls below the LOS threshold. In this case, the signal power cannot be included in the failure detection process because it is propagating in the other direction. Although this places greater dependence on the OSC reliability, it avoids shutting down the reverse path LSPs in the event of a false LOS alarm. This, in turn, will prevent the cascading shutdown scenario described in Section V. Given that modern laser diodes are quite reliable, in an OBS network, a counter propagating OSC may be preferable because it will prevent cascaded shutdowns.

Another issue that requires consideration is the impact of optical amplifier transients on the generation of false LOS alarms. As stated above, an LOS alarm is generated if the power in the optical fiber falls below the transmit "zero state" for longer than 100 μs. This problem has already been recognized by researchers and vendors. Solutions include the use of an OSC to compensate for amplifier transients [12], [13].

The issue of optical amplifier transients is addressed by most commercial amplifier vendors. For a modern optical amplifier, the typical total duration of the transient time arising from the addition or deletion of channels in a link is of the order than 100 μs or less [14]. This is also typically true for Raman fiber amplifiers [15]–[17]. The problem of false LOS due to amplifier transients will occur with the deletion of channels, because it is only in this case that any overshoot will result in a reduction of the power in the fiber being below the LOS threshold for 100 μs. However, given that the total decay time of the transient is of the order of 100 μs or less, it is extremely unlikely that the total optical power in the fiber will remain below the LOS threshold for a full 100 μs. If this were the case, false LOS alarms would also occur in SDH/SONET-based networks today. This is not the case in well-designed legacy networks.

VII. Conclusion

If optical networks are to evolve toward the IP over optical network paradigm of GMPLS, OBS, or OPS in which the SDH/SONET transport layer is removed, then a rethink of the APR mechanism, as described in the current standards, is required.

We have shown that if an OSC is not implemented, then during periods in which links are lightly loaded, an amplifier is likely to be unnecessarily shutdown with sufficient frequency to degrade the link's performance. Such shutdowns may have a significant impact on the performance of large regions of the network since other links and paths can also be impacted. Further, with the current rerouting protocols combined with the standard 100-s delay before a restart can be attempted, an optical link that was unnecessarily shutdown may become permanently unavailable.

To address these problems, it was shown that mandating at least one OSC as a monitor of path integrity (rather than just continuity check before restart) presents a viable amendment to the operation of APR and dramatically reduces the probability of unnecessary amplifier shutdown. To ensure the removal of single points of failure, multiple "permanently energized" channels will be required. An OSC plus one or more SDH/SONET channels can attain this. In an ASON, using an associated Data communications channel is also an option. When implementing this solution, the relative merits of copropagating and counter-propagating OSCs need to be considered.

Consideration of using the optical network control plane to prepare the optical amplifier monitor points for lulls in traffic indicates that this approach may not be practical.

Irrespective of the approach adopted, the reliability of the APR in high-capacity high-power optical communications systems cannot be compromised.

Appendix

The derivation of (1) is as follows. Let $X \in \{1, 2, \ldots\}$ be the random variable counting the number of de-energized periods up to and including a de-energized period lasting for more than τ seconds. The random variable X also counts the final de-energized period lasting for more than τ seconds. A de-energized period lasts for more than τ seconds with probability $e^{-\lambda\tau}$; therefore, X is geometrically distributed with parameter $e^{-\lambda\tau}$ and the expectation of X is given by $E(X) = e^{\lambda\tau}$.

Consider the Markov process with states given by the number of busy wavelengths. Let π_n, $n \in \{0, 1, 2, \ldots, N\}$, be the stationary probability that n of the N wavelengths are busy. Let B and I be the mean time that the fiber is energized and de-energized, respectively. The proportion of time that the fiber is de-energized is given by

$$\pi_0 = \left(\sum_{n=0}^{N} \frac{\rho^n}{n!}\right)^{-1} = \frac{I}{(B + I)}. \tag{3}$$

Rearranging (3) and noting that $I = 1/\lambda$ gives

$$B = \frac{1}{\lambda}\left(\sum_{n=0}^{N} \frac{\rho^n}{n!} - 1\right). \tag{4}$$

The time between unnecessary shutdowns T, given in (1), corresponds to the mean time between the start of two de-energized periods lasting for more than τ seconds, which can be approximated by

$$(I+B)E(X) = \frac{e^{\lambda\tau}}{\lambda}\left(\sum_{n=0}^{N}\frac{\rho^n}{n!}\right). \qquad (5)$$

REFERENCES

[1] G. Bernstein, B. Rajagopalan, and D. Saha, *Optical Network Control: Architecture, Protocols & Standards*. Reading, MA: Addison-Wesley, 2004.

[2] K. Liu, *IP Over WDM*. Chichester, U.K.: Wiley, 2002.

[3] S. J. Ben Yoo, “Optical packet switching routers and networks: Technologies architectures and applications,” in *Proc. Optoelectronics and Communications Conf. and Conf. Optical Internet (OECC/COIN) Tech. Dig.*, Yokohama, Japan, 2004, p. 12.

[4] A. Zapata, M. Duser, J. Spencer, P. Bayvel, I. de Miguel, D. Breuer, N. Hanik, and A. Gladish, “Next generation 100-Gigabit Metro Ethernet (100 GbME) multiwavelength optical rings,” *J. Lightw. Technol.*, vol. 22, no. 11, pp. 2420–2434, Nov. 2004.

[5] IEC 60825-1, *Safety of Laser Products—Part 1: Equipment Classification, Requirements and User’s Guide*, 2001, International Electrotechnical Commission.

[6] A. Srivastava and Y. Sun, “Advances in erbium doped fibre amplifiers,” in *Optical Fibre Telecommunications IVA*, I. Kaminow and T. Li, Eds. San Diego, CA: Academic, 2002.

[7] I. K. Rottwitt and A. Stentz, “Raman amplification in lightwave communications systems,” in *Optical Fibre Telecommunications IVA*, I. Kaminow and T. Li, Eds. San Diego, CA: Academic, 2002.

[8] ITU-T G.664, *Optical Safety Procedures and Requirements for Optical Transport Systems*, 2003, ITU.

[9] *Telcordia GRE-253-CORE,* Issue 3.

[10] ITU-T Recommendation G.8080/Y.1304, *Architecture for the Automatically Switched Optical Network (ASON)*, 2001.

[11] ITU-T Recommendation G.807/Y.1302, *Requirements of an Automatically Switched Transport Network (ASTN)*, 2001.

[12] H. Lee, J. Bang, J. Ko, C. Kim, and I. Kim, “Dynamic gain control of booster amplifier (EDFA) using optical supervisory channel power adjustment in WDM transmission systems,” in *Proc. Int. Conf. ATM (ICATM)*, Seoul, Korea, 2001, p. 278.

[13] J. Shin, Y. Kwon, and J. Koo, “Optical supervisory channel subsystem for 1.6 T WDM transmission system,” in *Proc. 6th Int. Conf. Advanced Communications Technology*, Phoenix Park, Korea, 2004, vol. 1, p. 402.

[14] For example: Avanex “Pure Gain 500,” Northlight Optronics “PGE60850,” Motorola “OA500 Series.” Note: Refering to these devices does not imply any form of endorsement by the authors.

[15] L. Wang, B. Hwang, and L. Yang, “Gain transients in copumped and counterpumped Raman amplifiers,” *IEEE Photon. Technol. Lett.*, vol. 15, no. 5, pp. 664–666, May 2003.

[16] C. Chen, J. Ye, W. Wong, Y. Lu, M. Ho, Y. Cao, M. Gassner, J. Pease, H. Tsai, H. Lee, S. Cabot, and Y. Sun, “Control of transients effects in distributed and lumped Raman amplifiers,” *Electron. Lett.*, vol. 37, no. 21, pp. 1304–1305, Oct. 2001.

[17] K. Karasek and M. Menif, “Channel addition/removal response in Raman fibre amplifiers: Modeling and experimentation,” *J. Lightw. Technol.*, vol. 20, no. 9, pp. 1680–1687, Sep. 2002.

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