Performance Optimization of Dynamic All-Optical Networks

Richard S. Wolff, Kevin Repasky, Brendan Mumey, Adam Green, Wenhao Lin
Montana State University, Bozeman MT 59717
rwolff@montana.edu, repasky@coe.montana.edu, mumey@cs.montana.edu, ajgreen@rivers1.msu.montana.edu, lin@cs.montana.edu

Abstract: We explore and report on the temporal behavior of MEMS-based optical switching elements and optical amplifiers in multi-wavelength systems as may be utilized in next generation optical networks. The importance of this work is underscored by the growing use of dense wavelength division multiplexing (DWDM) in conjunction with dynamically controlled optically transparent network elements. Switching, using MEMS technology, has taken on an important role in supporting dynamic network reconfiguration. Such networks typically include optical amplifiers, and multiple wavelengths are amplified by a single network element. The combination of MEMS switching with optical amplifiers and other active elements provides new challenges in overall system design, as the millisecond switching time of MEMS fabrics is comparable to the excited state lifetime in Erbium doped fiber amplifiers (EDFAs), thereby leading to potentially undesirable gain fluctuations and cross talk. Our observations of such transients show durations ranging upwards of 20 milliseconds and amplitudes of up to 2 dB, with transients affecting both switched and unswitched wavelengths. These effects can lead to degradation in end-to-end system performance, as measured by bit error rate (BER). This problem is particularly important for future optical networks where burst switching and packet switching, in addition to circuit switching will generate transients on finer time scales. We first examine and report on the temporal behavior of MEMS-based optical switching elements and optical amplifiers in multi-wavelength systems as may be utilized in next generation optical networks. Our experiments utilize commercially available MEMS switching fabrics and EDFAs, configured to emulate a realistic metro area network. We then use these experimental results to examine and compare several approaches to optimizing end-to-end performance. We explore a proactive approach, where routing and wavelength assignment decisions are based on algorithms that optimize the distribution of traffic, thereby minimizing the impacts of transients due to bursty traffic on unswitched traffic. We propose several algorithms for routing and wavelength assignment specifically designed for dynamic, all-optical networks, where wavelength conversion is not available and quantify the reduction in performance impairments that can be achieved.

@2005 Optical Society of America

OCIS codes: (060.0060) Fiber optics and optical communications; (060.4250) Networks

1. Introduction

Future generations of optical networks are moving away from static path and wavelength assignment to optical circuit switching, burst switching and packet routing in an effort to meet demanding cyber infrastructure needs. The time scales for changes in traffic, as measured in terms of paths and wavelengths in use, are moving from days or minutes for circuit assignments, seconds or milliseconds for burst switched services, and microseconds to nanoseconds for optical packet routing. These multiple wavelength, all-optical networks will use optical switches and optical amplifiers to provide on-demand resource allocation to meet demanding application requirements and to improve the overall network performance. Several methods of switching in the optical domain have been developed and are now reaching sufficient maturity to enable network grade products. Switching, using MEMS technology, has taken on an important role in supporting dynamic network reconfiguration for rapid provisioning, just in time services, quality of service management and restoration and will play an important role in the next generation optical networks. Such networks will include optical amplifiers for line amplification, power leveling and pre-detection gain, and, in these networks, multiple wavelengths are amplified by a single network element [1]. The temporal behavior of optical amplifiers has been studied. Early measurements of optical signal power level and the error rate in dynamic, all-optical WDM networks were carried out and reported for the MONET testbed, and these data indicate that significant transient effects are encountered [2]. Bit error rate degradation and framing errors (where SONET transmission was used) were associated with these phenomena, even with gain-clamped optical amplifiers.
in place. Gain fluctuations in EDFAs carrying multiple optical channels have been measured [3] and simulated [4-5], and several techniques have been developed to provide clamping, but ringing phenomena persist [6] and can contribute to degraded end-to-end performance. Furthermore, chains of network elements tend to extend the time constant for transient decay [7]. Recently reported analytical studies of optical system dynamics shows how power transients can propagate on millisecond time scales [8]. Similar effects have been examined and noted with Raman and Solid state optical amplifiers.

Transient effects tend to propagate through the network with the number of amplifiers and other network elements, as well as the number of wavelengths passing through the elements, as factors in determining end-to-end performance. The total power of an optical line amplifier (OLA) is shared among the optical channels, and changing the number of wavelengths then requires changing the amplifier pump power to maintain constant power per wavelength. Experiments have shown that with an EDFA such adjustment requires over 100 μsec to begin the correction and over 5msec for completion [6]. During this interval, power variations in one channel modulate power in other channels. If these excursions are large, amplifier saturation can occur, and end-to-end performance may be affected on all of the channels. Results of experiments where 1, 4 and 7 channels are dropped show that the power transients in the remaining channels are both large (several dB) and fast (100 μsec or less. [5]. The number of EDFAs and the number of wavelengths also contribute to the effective time constant of transients in WDM networks [7]. For instances where servo-controlled attenuators are used within WDM network elements as power equalizers, transient effects due to adding and dropping channels passing through EDFAs can be pronounced in magnitude and duration, ranging up to twice the servo response time and affecting multiple optical channels [8].

Transients due to the behavior of the MEMS switch fabric are dependent on several factors, including the physical characteristics of the mirrors, which typically have resonant frequencies of 1kHz and the drive waveforms. The Q of the mechanical structures can be high, so moving the mirror elements quickly can excite resonances that translate to ringing in the optical signal power [9]. Switch designers optimize the drive waveform to minimize the ringing effects, defining a switching time in terms of the interval between the initial application of the electrical signal and the moment where the optical power remains within 90% of its final value. This interval is typically in the order of milliseconds, but can range upwards of tens of milliseconds if the drive signal is not optimized. The combination of MEMS switching with optical amplifiers and other active elements provides new challenges in overall system design, as the millisecond switching time of MEMS fabrics is comparable to the excited state lifetime in EDFAs, thereby leading to potentially undesirable gain fluctuations and cross talk [10].

Both proactive and reactive techniques have been proposed to control and minimize the effects of switching transients in optical networks. Proactive techniques include damping within the MEMS switch, accomplished through mechanical construction and by shaping the temporal structure of the switching voltage. Routing and wavelength assignment (RWA) strategies also fall into the proactive classification. Reactive approaches include amplifier gain control, which can be accomplished using electrical and optical feedback loops. Both “feed forward”[11] and “feed back” [12] optical amplifier gain control strategies have been reported and each has its merits. The feed back approaches typically involve use of an optical pilot signal that propagates through the amplifier, or chain of amplifiers. While this technique has shown promising results in mitigating transients induced by optical bursts, it has the disadvantages of consuming a dedicated wavelength and some of the amplifier power.

RWA strategies for networks with and without wavelength conversion at intermediate nodes have been studied and presented in the literature. However, this work does not take into account the effects of the physical layer of the network on the RWA strategies. Furthermore, these approaches typical consider relatively static conditions and do not consider physical layer effects that may be introduced by circuit assignment, burst or packet switching in the optical domain. Network and routing models typically assume that there is no signal impairment along the optical path and only the logical aspects of the routing problem are considered. However, in evaluating a potential lightpath, there are numerous physical characteristics and effects that may affect the end-to-end performance of the signal and hence may need to be addressed in the route selection procedure. In addition to optical power loss, factors that may be important include self-phase modulation, group velocity dispersion, polarization mode dispersion, optical filter and optical amplifier gain flatness and phase response [13]. A good review of issues affecting routing in the optical layer is discussed in [14], but applies to relatively static conditions and does not address transient effects. The effects of crosstalk, amplifier noise, polarization mode dispersion and filter concatenation have been modeled and recently reported in [15], and these results show how physical layer behavior can affect throughput in terms of blocking probability. A link design concept has been proposed in [16], whereby normalized transmission sections are defined to truncate the additive non-linear effects in long haul WDM systems. Algorithms that incorporate power considerations in RWA for all-optical networks have been reported [17], but address only static network conditions. In well engineered and managed optical networks, many of these factors are taken into account by periodic
dispersion compensation and power control techniques, particularly where the network topology and light path assignments are relatively static, and the network operates in steady state.

There have been several efforts to address routing and wavelength assignment under dynamic conditions, but only a limited number of physical constraints have been considered. The limitations imposed on RWA by power level constraints have been recently explored [18], where algorithms for dynamic routing and wavelength assignment were developed to accommodate degradation in optical signal quality due to imperfections and losses in optical network components. In this work, the authors focus on developing algorithms that provide suitable light paths by suppressing and avoiding optical amplifier overload and saturation. Such effects would lead to reduced signal power per optical carrier with the consequence of unacceptable end-to-end performance. Another recent study addresses the effects of accumulated noise along light paths due to cascades of optical amplifiers [13]. This work develops a methodology of predicting end-to-end path performance measured in terms of bit error rate, using factors such as receiver sensitivity and noise characteristics of optical amplifiers along the path. The study addresses only the steady state case, and does not consider the methods of dynamically selecting routes as wavelengths are added or dropped. An optical routing protocol that utilizes measured information about signal quality along potential light paths has recently been proposed [19], but this approach does not consider transient effects and requires specialized measurement equipment. A need exists for a RWA strategy that takes into account the dynamic conditions that affect the physical layer performance.

In this paper we first report measurements of the temporal behavior of optical signals in an all-optical WDM network emulation consisting of a prototype MEMS switch, provided by the DARPA/NSF Photonic Technology Access Program (PTAP) and several EDFAs. The test bed can be configured to emulate a large-scale network by utilizing different switch ports to serve as independent optical nodes. The results indicate the temporal constraints necessary to assure that interference between bursts and switched channels on different wavelengths is minimized. We then address the use of RWA techniques to distribute dynamic traffic throughout the network and examine resource utilization efficiency and the effects of switching transients on the error performance. We use the measured switching transient effects to characterize the impairments introduced by temporally dynamic optical traffic. Our results are specific to fast circuit or burst switching cases, but the approach can be generalized to more transient optical packet switched networks.

2. Transient measurements
The optimization and performance of the physical layer of a switching network will be studied using the optical test bed currently operating at Montana State University and shown schematically in figure 1. Four commercial lasers with wavelengths of 1550.92nm, 1554.14nm, 1557.37nm, and 1560.61nm are currently used in this test bed. These four lasers are sent through an 8x8 MEMS-based optical switch that is controlled via a computer. After the MEMS switch, the four wavelengths are combined onto a single fiber.

Fig 1. Dynamic all-optical network test bed

The variable optical attenuator allows us to mimic the losses in a metro area or long haul optical fiber network. A commercial EDFA is used to provide optical amplification at the multiple wavelengths. Finally, a de-multiplexer is used to separate the four wavelengths that are incident on four separate detectors. The test bed can be configured to emulate a multi-node network by routing selected wavelengths through the switch and additional amplifiers multiple times. A picture of the optical test bed setup is shown in figure 2. This work has been reported elsewhere and we summarize the key results here [20].
We first characterized the temporal behavior of the MEMS switch without amplifiers. Measurements of power versus time for switch closures and openings were made for each of the 8 provisioned switch ports, and typical results for a single switch closure (power-off to power-on state) are shown in figure 3. The light power reaches the 90% level in about 2msec, but considerable ringing (up to 23% of mean power) persists for 10msec and damps to a few percent of mean power in 20msec. The data also show a periodic structure, with a period of about 2msec. Results for switch opening measurements (power-on to power-off state) showed a power reduction to 10% of the on level in 1msec and an absence of the ringing. These results are consistent with the assertion that the ringing is a manifestation of the mechanical resonance of the MEMS mirrors.

In a second series of experiments we explored the temporal behavior of the EDFA without the MEMS switch. In these measurements we directly modulated the laser source at a 1MHz rate and detected power level transients with durations of microseconds to a few milliseconds and amplitude excursions of about 20% of average power level as reported elsewhere [2-3]. Hence in terms of duration, the transient response of the combination of MEMS switches and EDFAs would be dominated in the long term by the MEMS behavior, for power-off to power-on state changes, but the amplitude of the EDFA and MEMS switch transient effects would be additive in the initial few milliseconds. For power-on to power-off state changes, the durations of the EDFA and MEMS switch transients are comparable.

Experimental results obtained from the test bed described by figure 1 show transient behavior that might be experienced in an optical network with dynamic resource allocation are shown in Figure 3. In this example, two signals $\lambda_1$ and $\lambda_2$ passed through an EDFA operating at saturation. The MEMS switch was used to turn $\lambda_1$ on and off, introducing an overall level shift in $\lambda_2$ as well as a transient with a frequency of about 1kHz corresponding to the resonant frequency of the switching mirrors. This ringing lasted for approximately 20msec. The transient amplitude corresponds to up to 1.5 dB excursions in the power level of the un-switched signal, sufficient to introduce bit errors for the 20msec duration of the transient. Figure 3a illustrates the effects of a single switch node and amplifier. Figure 3b shows the effect of passing the signal through two switching nodes and amplifiers.
Additional experiments were conducted using multiple switch ports to emulate a multi-node network, with the signals passing through combinations of switch ports, combiners and amplifiers, and similar transient effects were observed. Figure 4 shows the results of an experiment where a network consisting of two switch nodes, and two EDFAs with a switched and unswitched wavelength. The figure shows the transient effect, measured on the unswitched wavelength, after passage through all nodes. The EDFAs were in saturation in this experiment, characteristic of typical network operation, where maximum gain is required. Power excursions in excess of 1.7dB are observed in the first 8msec, and the transient effect continues for more than 25msec.

![Fig. 4. Transient observed on unswitched wavelength in two-node network](image)

These results show that significant transients in switched and unswitched light paths can be induced in an all-optical network comprised of MEMS-based switch nodes and EDFAs. A single switching event can result in a transient effect with duration in the range of 25-30msec that could disrupt communications. Several factors require further consideration in estimating the impact of these effects. First, as the number of wavelengths sharing an amplifier increases, the magnitude of the transient induced by a switching event on one signal will be distributed among the other non-switched signals, lessening the impact on a particular unswitched signal. This effect is well known in multi-wavelength add-drop systems. However, this sharing “gain” is mitigated by the possibility that each of the wavelengths could potentially be independently switched, and the collective effect of all the transients could result in a noise-like environment that would cause degradation in the end-to-end system performance. This would be particularly important for applications that involve optical burst switching, where the MEMS fabric is being continuously reconfigured at millisecond rates. At high burst rates, the additive effect of the transients would be significant and could lead to serious loss of throughput.

3. Routing and Wavelength Assignment Strategies

In the previous section, we reported performance issues associated with the physical layer of the network. In this section, we discuss methods and results of using RWA strategies to maximize performance and utilization of next generation networks. Unlike previous work, we address RWA strategies that take into account the performance of the physical layer, particularly in regard to transients.

Extensive work has been done in network topologies where wavelength conversion is possible at intermediate nodes, thereby alleviating the wavelength continuity constraint [21]. The extension of MPLS to include optical routing (e.g., GMPLS) takes into account certain attributes associated with optical networks [22-24], and a technique to take these factors into account in routing has been proposed as a modification to SPF algorithms [25]. However, the light path characteristics explicitly identified in the GMPLS framework are logical and ideal: interface switch capability, interface bandwidth, link protection type, traffic engineering metric, hop count limit, priority and preemption, etc. There is currently no inclusion of optical layer behavior and performance factors such as number of wavelengths on a fiber, signal power levels, noise levels, end-to-end bit error rate, etc. These factors could be constraints in selecting optical paths and should be considered in RWA.

Our own research on all-optical network routing has led to the development of two new algorithms for RWA. We address the case where a single wavelength must be used end-to-end (e.g., no wavelength conversion is possible) and have designed an algorithm that is particularly well-suited to enable highly-dynamic RWA anticipated in burst-mode and customer-controlled all-optical networks [26]. This new adaptive routing algorithm is inspired by the lexicographical optimization idea [27]. We are mainly concerned with how to compute a path based on the current network state that decreases system connection request blocking probability. After path computation, reservation signaling procedures are executed to establish a connection. Our Lexicographic Routing Algorithm (LORA)
efficiently spreads the traffic load among all links and allocates wavelengths efficiently. As described below, this approach spreads the transient effects across a maximum number of links, thereby minimizing the number of transients on any single path, reducing disruptions. In LORA, we build a vector whose elements are the usage of each link in a network. Our objective is to find a route for a connection request such that the resultant vector after route decision is lexicographically smallest. This algorithm distributes traffic evenly on all links. In our simulation tests of LORA, we used the 16-node NSF network as our experiment network topology and assumed no wavelength conversion. We further assumed that each link has 10 wavelengths. We used the Backward-Reservation method [28] and First-fit wavelength allocation [29] for the simulation. We compared the performance of LORA with three other algorithms: shortest path, minimal cost path with cost \( (l) = Cl \) (named Least Congested (LC) here), and minimal cost path with cost \( (l) = \exp(Cl) \) (named Enhanced Least Congested (ELC) here). Figure 5 shows the results of the comparison.

![Fig. 5. Performance comparison. X axis is traffic load, in Erlangs and Y axis is blocking probability](image)

The results obtained with LORA are significantly better than those obtained with least cost (LC) methods, with at least a 25% reduction in blocking probability. This work forms a foundation for our research designing RWA algorithms under additional constraints such as link performance, transient effects in switches and amplifiers, and other physical layer factors.

We have developed a second algorithm that utilizes continuous time (C-T) Markov modeling to increase the probability of successful (e.g., low contention) wavelength reservation in the presence of multiple, competing connection requests. In the back-forward reservation method, several ‘probe’ messages may see the same free wavelengths on a link as they propagate from source to destination. If competing destinations choose the same free wavelength, then confliction occurs. Our new algorithm, MBR, tries to decrease the chance of such confliction. We assume the destination nodes use first-fit wavelength selection and use a C-T Markov chain to model each optical link. Each state of the Markov chain corresponds to how many wavelengths are used on a link. The parameters of the chain (e.g., transition rates between states) are obtained by network monitoring by switch nodes. By transient analysis [30], we can predict at some arbitrary time T, the probability that a wavelength is free on a link. By using an independency assumption, we can predict the probability that a wavelength is free on a path. When a ‘probe’ message arrives at a node, we predict the wavelength that is mostly likely to be used by first-fit. When other ‘probe’ message arrives, this wavelength will be marked as ‘Guessed Busy’. Then the destination node will find three sets of wavelengths in the received ‘probe’ message, ‘Busy’, ‘Guessed Busy’ and ‘Free’ instead of just two as in an ordinary reservation protocol. The destination node will choose a wavelength from the ‘Free’ set. To evaluate this approach we have run MBR on the NSF network and another mesh network. The benchmark algorithms include Backward Reservation with First-Fit (FF), Backward Reservation with Random assignment (RND, which will randomly select a free wavelength) and Backward Reservation with enhanced Random assignment (RND3, which will randomly select a wavelength from the first three free wavelengths). We use these three algorithms because they are easy to implement and have comparatively good performance. In our experiments, we assume no wavelength converters exist in the network and each link has 10 wavelengths. Our simulation results, shown in figure 6, indicate that in some simple topologies, this algorithm can decrease confliction dramatically.
These results demonstrate that wavelength selection contention in highly dynamic conditions can lead to significant blocking and inefficiencies unless a well-designed wavelength assignment algorithm is utilized. For a network load of 30 Erlangs, use of MBR decreases the blocking probability by 50%. We have run simulations with more wavelengths per link and for a more complex, mesh network topology and find similar results.

4. Discussion
In this section we assess the combined benefits of proactive routing and wavelength assignment in mitigating the deleterious effects of switching transients. We begin by considering a simple model in which the additive effects of multiple switched wavelengths on a link are characterized by the transient time $T$ measured and discussed in section 2. We assume a burst duration $D$ and the number of switched wavelengths on a link $N$, and calculate the fraction of time when the link would be affected by transients. The results are shown in figure 7, for two cases: fast bursts, with a duration of 1 second, and slowly changing bursts, or fast switching, with a duration of 10 seconds.

These results indicate that as link utilization increases, the fraction of time could be affected by switching-induced transients can become significant, unless RWA strategies are used to spread the traffic uniformly across available links. The data in figure 7 present a “worst case” scenario in that we are assuming that the disruptions caused by switching transients are non-overlapping. This would not be the case in synchronized burst switched networks.

We assess the value of using routing strategies to mitigate the effects of transient-induced impairments by comparing the number of wavelengths assigned to links in a typical network as a function of overall load. Following the method described above, we model the 16-node NSF network and calculate the average number of wavelengths used on the busiest link, as the busiest link would be most vulnerable to impairments. The results of the simulation are shown in figure 8, where we compare LORA with other route selection algorithms. The results indicate that for light to moderate traffic levels (e.g., less than 90 Erlangs on this 16-node network), LORA outperforms all the other
approaches, measured in terms of the average number of wavelengths used on the busiest link. Compared to Least Cost path routing, LORA yields up to a 25% improvement.

We combine this results with the blockage estimates in figure 7, and find that for a fast circuit switched network, with wavelength utilization of five (or 50% of available wavelengths), the probability that a burst will be affected by a switching transient can be reduced to less than 1% under “worst case” conditions.

The MBR algorithm optimally picks the wavelength along the selected route to minimize the probability that one or more other RWA processes conflict during the selection process. This results in maximum efficiency in network resource usage, as measured by overall traffic capacity. By minimizing conflicts in combination with spreading the traffic uniformly across the network, the disruptive effects of switching transients are further reduced. Additional consideration can be given to specific wavelength selection in the MBR algorithm based on particular properties of links. For example, the algorithm can be “tuned” to select wavelengths that are optimally spaced to reduce inter-modulation effects by adjusting the weighting factors. Similarly, the effects of gain slope or other wavelength dependent factors could be incorporated into the MBR algorithm to optimize performance based on physical layer characteristics.

4. Conclusions

We have shown, through measurements with optical network components configured to emulate a dynamic, MEMS-switched all-optical network, that transients induced by switching, combined with cross talk that naturally occurs in EDFAs, can lead to significant transient effects on both switched and unswitched signals. The magnitude and duration of these effects range up to 30% of the average power level and persist for tens of milliseconds. We then have demonstrated that routing algorithms designed to optimize network utilization by spreading traffic across network resources and minimizing wavelength assignment confliction can be used to proactively reduce the probability that switching transients will result in outages in burst-switched all-optical networks. We have quantified our results by combining performance measurements made using a MEMS switch and EDFAs in an network emulation with simulations of network blockage under a range of traffic load conditions calculated using existing RWA algorithms and our new lexicographic routing algorithm and Markov-based wavelength selection algorithm. Our results indicate that substantial performance improvements can be achieved using these proactive techniques.

5. References