Overview of Technologies for Use in All-Optical Packet Switching Networks

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1. Introduction

Over the last several decades, as the Internet has grown in popularity and utility, demand has grown tremendously for increased network capacity. Furthermore, the need for faster and faster transmission speeds is not likely to slow in the coming years as Internet Protocol Television (IPTV) and high-definition TV (HDTV) begin to see widespread adoption. Transmission of high-definition images is expected to become a significant portion of network traffic in the future. According to Namiki and Shioda (2010), HDTV requires transmission rates in excess of 1.5 Gb/s, while real-time transmission of super high-definition images including 4k Digital Cinema and 8k Super High Vision (SHV) require transmission rates as high as 72 Gb/s.

To meet this insatiable appetite for network capacity, providers have increasingly switched to fiber-optic communication channels which may yield bandwidths in the range of 40 THz. However, current network technology requires that optical signals be converted to the electrical domain for routing and control. Once this processing is accomplished, the signals must be converted back into the optical domain. Since the speed of the electrical domain is limited to 40 Gb/s, this process results in a significant bottleneck for network transmission. A number of techniques have been proposed for overcoming this bottleneck. Some promising solutions have included hybrid optical circuit switching (OCS) paradigms that use a combination of optical switching and electronic switching as well as all-optical burst switching (OBS) paradigms. However, Pellicer, Redondo, and Zaballa (2009) believe an even better solution may be found in all-optical packet switching networks. To implement such networks, a number of enabling technologies are necessary. This paper will provide an overview of optical switching networks and will examine key technologies used in the implementation of all-optical packet switching networks such as optical routing, optical buffering, and optical labeling. Additionally, some advanced topics will be covered such as scheduling, virtualization, and security. Finally, a case study will be considered for an avionics network.

2. Overview of Optical Switching Networks

To highlight the advantages offered by optical packet switching (OPS) networks that route signals entirely in the optical domain, consider briefly two other optical switching paradigms: OCS and OBS. First, consider circuit switching, a networking methodology that involves setting up a dedicated communication channel between two nodes. The channel is used exclusively by the nodes to exchange data and is dismantled after communication is complete. On the other hand, packet switching is more flexible, allowing many nodes to communicate simultaneously. In packet switching data is placed in packets which may take different paths through the network to reach their destinations. A significant limitation of circuit switching compared to packet switching is its inefficiency in dealing with files of widely varying sizes, a common occurrence with internet traffic. To overcome the limitations of circuit switching in routing internet traffic, Namiki and Shioda (2010) have proposed a hybrid technique that constructs a local area network (LAN) using a single-star topology. At the center of the LAN is an optical switch which implements OCS, setting up dedicated optical connections with nodes in other networks. Connected to the optical switch are a number of electronic packet switching (EPS) nodes that route traffic locally. While Namiki and Shioda (2010) have shown that performance of this hybrid network is superior to that of either OCS or EPS networks acting individually, the necessity of converting optical signals to and from the electronic domain still presents a significant bottleneck.

A second alternative to OPS is burst switching. Bhusari and Sahu (2013) have proposed a system where an OBS node is placed at the edge of a network to collect traffic and group it into variable sized bursts that are sorted according to destination address. The OBS node then sets up a connection with the destination node by determining routing and wavelength allocation needs and then sending a control packet to the destination node to set up a buffer free optical path. Control packets are handled on a separate path from data. Once the connection is set up, the OBS node sends the data burst. This method has the advantage of not requiring significant buffer space, a resource generally in short supply for optical networks. However, the control data is managed in the electronic domain, once again presenting a bottleneck for transmission speeds.

The advantages of optical switching are clear, but the networks considered so far are each subject to inefficiencies, primarily due to switching between optical and electronic domains and limitations in dealing with variable internet traffic. To overcome these bottlenecks, an all-optical packet switched network is needed. Figure 1 shows one possible implementation of an all-optical packet switching router. The depicted implementation is based on a design proposed by Pellicer, Redondo, and Zaballa (2009).

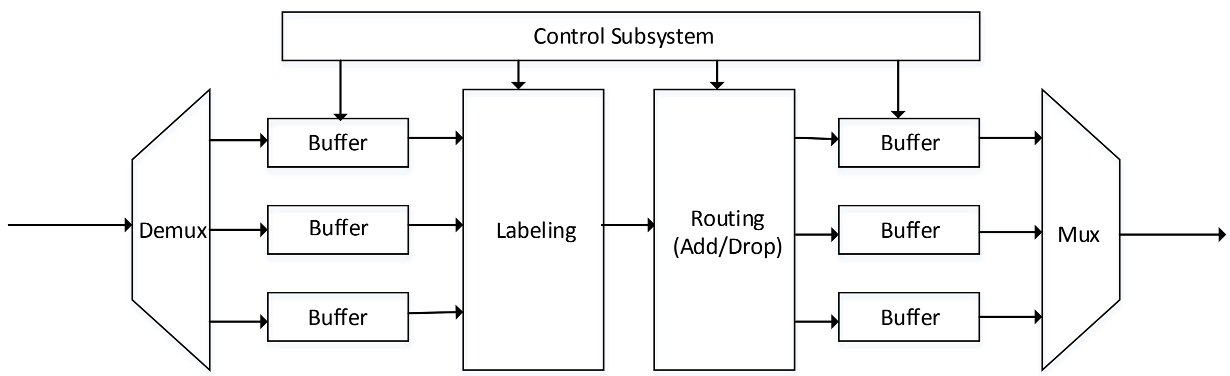

Figure 1: Packet Switching Router

As shown in the figure, an OPS router requires components for multiplexing and demultiplexing. These components separate and combine individual optical signals that are transmitted using an optical communication waveform such as Wave Division Multiplexing (WDM), Optical Orthogonal Frequency Division Multiplexing (OOFDM), or Optical Time Division Multiplexing (OTDM). In addition optical buffers are necessary to store light signals during control processing and resolution of packet conflicts. This control processing is represented by the control subsystem block in the diagram. Efforts to simplify control processing and potentially to conduct such processing entirely in the optical domain are aided by the use of optical labels. The labeling component manages these labels which serve to minimize processing time and provide quality of service (QoS) information. After the labeling stage, another component routes the packets. During this stage new packets are added to the network path, and some packets are dropped, meaning they are sent to other network paths. The components making up an OPS router will be considered in more detail later.

3. Overview of Optical Waveforms

Before examining the various components that are used in construction of OPS routers, a brief overview of some prevalent optical waveforms will be beneficial. First, consider WDM, which Ishio, Minowa, and Nosu (1984) describe as a transmission mechanism by which a number of optical signals of different wavelengths are simultaneously sent over the same optical fiber by multiplexing them together. This allows the total available optical frequency bandwidth to be used to transmit data. The process is similar to frequency division multiplexing (FDM) done in the electrical domain. The multiplexed signals are later separated by a demultiplexer that selectively filters the combined signal according to wavelength.

An alternative to WDM is OTDM. According to Eisenstein, Korotky, and Tucker (1988), OTDM is an extension of the concept of time-division multiplexing from the electrical domain to the optical domain. OTDM is the time domain counterpart of WDM. In this transmission mechanism, a series of optical data streams are alternately sampled and combined into a single, higher bit-rate stream. Essentially, instead of splitting the available frequency between the signals, the available time is split between them. On the receiving end, a demultiplexer reconstructs the original lower-rate bit streams by separating the transmitted high-rate stream.

A final waveform to consider is OOFDM. Like WDM and OTDM, OOFDM is an extension of an electrical domain concept into the optical domain. Wu and Zhang (2011) state that OOFDM utilizes the technique of Orthogonal Frequency Division Multiplexing (OFDM). This waveform is similar to FDM with the major difference being that the frequency bandwidth is more efficiently used. This is accomplished by overlapping the spectrum of the individual carriers, a feat made possible by spacing the signals such that they are orthogonal. Implementing OFDM requires use of the discrete Fourier transform (DFT). OOFDM offers the potential of even greater network capacity than WDM and OTDM at the cost of greater complexity.

The use of the aforementioned optical waveforms allows many signals to be multiplexed together. In doing this optical system designers gain many advantages such as increased data capacity, bidirectional transmission, the ability to transmit different types of signals simultaneously, and flexibility. These qualities are fundamental in enabling all-optical networks and achieving OPS. In most cases more complicated waveforms are more difficult to process, leading to more challenges to overcome in creating all-optical networks. Rather than elaborating on these challenges, the assumption is made that an all-optical packet switched network could be implemented using any of these waveforms. In discussing the various technologies required to enable these networks, the underlying transmission waveform will be generalized to WDM for the sake of simplicity.

4. Optical Logic Gates and Memory Components

One underlying technology that could become a crucial enabler of all-optical networks is the creation of optical switches, which could be used in logic gates and memory components. Such technology could ultimately result in not just optical networks, but entire optical computing platforms. However, for our purposes optical switches are only considered for their potential use in network specific components such as control logic and buffering. A number of different techniques are being developed with the potential to provide these much desired components. A comparison of two such methods follows.

One promising avenue of research that may eventually yield economical optical memory and logic gates involves the use of photonic crystals constructed within silicon chips. A photonic crystal is a dielectric nanostructure with a periodically varying refractive index. The properties of photonic crystals are such that they can act as optical filters, blocking certain wavelengths of light and creating photonic band gaps. Additional useful characteristics can be achieved by introducing localized defects into the crystals. The potential uses of photonic crystals in the area of optical networking are wide ranging, and they will be encountered again in discussion of other networking components. Their use in creating optical memory has been studied by Kuramochi, Mitsugi, Notomi, Shinya, and Tanabe (2005) who have demonstrated all-optical memory operation in frequency bands used for telecommunication. The device was constructed on a silicon chip and designed to be optically bistable. This means it has two possible resonant transmission states that are stable. These states can be selected by providing different inputs and are used to store binary data. One state represents logic “0” and the other represents logic “1.” Kuramochi et al. (2005) have demonstrated through experimentation that their device is indeed bistable with one transmission state at 1536.47 nm and another at 1569.70 nm. Further, they have performed read and write memory operations by applying input pulses to their chip. Their research suggests that a large number of such devices could be efficiently cascaded on a single silicon chip and mixed with traditional electronic CMOS logic. A photonic memory device such as that suggested by Kuramochi et al. could prove highly valuable in the development of optical buffers and optical processing components for performing operations such as the discrete Fourier transforms needed for OOFDM.

Another area being investigated for use in optical logic and memory components is that of molecular switches. Research conducted by Giordani and Raymo (2002) has demonstrated that arrays of independent photoactive molecular switches with optical inputs and outputs are able to perform logical operations such as NAND, NOR, and NOT operations equivalent to those of electronic logic gates. These molecular switches are synthesized using a chemical method that results in a substance that switches states upon exposure to different wavelengths of light. The purple merocyanine (ME) state happens to absorb 563 nm wavelength light, while the colorless spiropyran (SP) state releases it. Giordani and Raymo (2002) suggest that the properties of their molecular switch theoretically allow optical inputs to be transduced into optical outputs within picoseconds. By producing arrays of independent switching devices, various logic gates can be constructed, allowing optical signals to be gated in response to other optical signals. Giordani and Raymo (2002) conclude that molecular switches are a versatile and powerful method for constructing optical logic gates. However, they caution that further research is necessary to assess potential hurdles such as limitations in practically achievable switching speeds and photodegradation of the molecular components. Ultimately, if these limitations can be overcome, molecular switches may prove vital in the design of control logic for optical networks.

5. Optical Buffers

According to Pellicer, Redondo, and Zaballa (2009), the task of creating optical buffers is among the most challenging in designing OPS networks. Optical buffers are mainly necessary to store optical packets while routing decisions are being made and while other packets are being transmitted. Early attempts at developing them have focused on mechanically switching between variable length coils of fiber optic cabling which delay the light waves by different amounts. Unsurprisingly, this approach is cumbersome and inefficient. Fortunately, a newer technique referred to as slow light is emerging as a viable alternative, offering faster access, fully-integrable buffers, and continuously tunable delays. The basic operating principle of slow light, as reported by Boyd and Narum (2007), involves manipulating the group index n_g of the material through which optical signals are passing. By increasing the group index, the group velocity of the signals can be decreased. Changing the group index is accomplished using behaviors predicted by the Kramers-Kronig relations. By achieving atomic resonance, the refractive index of a medium can be rapidly varied over the frequency spectrum, which results in an associated change in the group index.

Pellicer, Redondo, and Zaballa (2009) document a host of different ways to implement slow light optical buffers. The methods fall into two general categories: material-based systems and engineered structures. While all of the techniques depend on the same basic principles to operate, the specific means employed to achieve atomic resonance varies greatly between the different methods, and each has a different set of advantages and limitations. The material-based methods include Electromagnetically Induced Transparency (EIT), Coherent Population Oscillation (CPO), Brillouin Raman scattering, metamaterials, and plasmonics. The engineered structures include photonic crystals, micro-ring resonators, and cascaded gratings. Material-based devices tend to underperform engineered structures for high-bandwidth signals, because they have narrow widths and tend to suffer more from the effects of dispersion. Additionally, in material-based devices, waveguide loses are linked to inherent attributes of the materials, while in engineered structures, waveguide loses can be improved with better fabrication methods.

As with optical logic gates and memory devices, photonic crystals are considered to be the most promising technology for implementing slow light buffers. The fabrication process for photonic crystal slow light buffers, as detailed by Pellicer, Redondo, and Zaballa (2009), involves creating defects in the crystals that result in defect modes where certain wavelengths of light that are within the photonic bandgap are able to pass through the defective portion of the crystal. This process effectively creates a waveguide where the light is confined by the photonic crystal's bandgap. Light passing through the waveguide experiences strong dispersion, which causes slow light along the photonic band edge. The design is very flexible and has the advantage that it may be fabricated using silicon chips. To date, buffers storing up to 12 signal bits have been demonstrated. However, as with other slow light techniques, photonic crystals suffer from dispersion and loss. These effects result largely from scattering caused by structural disorder and material absorption, and improved manufacturing methods may well overcome these issues. If these limitations can be overcome and larger buffers are achieved, photonic crystal slow light buffers have the potential to play a key role in enabling all-optical packet switched networks.

6. Optical Labeling

In addition to optical buffering, another vital element in optical networking is providing routing and control information. A common method for achieving these capabilities is to use optical labels. When labels are used, routers along the network path must perform a number of tasks including extracting the label from the signal, processing the label, routing the payload, and swapping the label for a new one. According to Chang, Chowdhury, Jia, Yeo, and Yu (2006) a variety of methods exist for generating, extracting, and removing optical labels. Some of them require conversion into the electronic domain for label processing, while others are all-optical. Packet switched networks are particularly hard to implement using all-optical methods as they require more complex packet forwarding rules. Most of the techniques offer the advantage of separating the label, analogous to a packet header for OPS, from the payload for processing. This means that the payload can be routed without modification, limiting the optical to electronic conversion to the label.

Chang et al. (2006) suggest three basic approaches for attaching labels to payloads. The first is time-serial labeling, where the label and the payload are sent to the router at different times. The time separation between them is known as a guard time. Keeping this time from varying as the packet is transmitted across the network is essential. Most time-serial labeling strategies require that the header be transmitted at a much lower bitrate than the payload, causing header processing to become a significant bottleneck. A number of methods exist for speeding up processing time. However, they require that header parameters such as bitrate, size, and modulation format be permanently fixed, reducing scalability and flexibility.

A second way to attach labels is to encode the label and the payload using different formats, transmitting them simultaneously. This has the advantage of allowing both to reside within the same wavelength, saving bandwidth. Though, this savings comes at the cost of additional processing complexity needed to separate the label from the payload on the receiving end. Label extraction methods vary depending on the type of encoding used. Some examples of encoding include intensity modulation (IM), frequency shift keying (FSK), differential phase shift keying (DFSK), amplitude shift keying (ASK), and polarization shift keying.

In contrast to this variable encoding technique, the third method for labeling involves transmitting the label on a different wavelength from the payload but using the same encoding. This can be done in two different ways. The first is out-of-band labeling which places the label in a separate wavelength channel from the payload, while the second is in-band labeling, which places the label in the same wavelength channel as the payload. Both methods allow the label and payload to be separated using optical filtering, and each has advantages and disadvantages.

After a label has been attached, and the packet has been transmitted to an intermediate router along the network path, the label must be swapped for a different one. Swapping a label involves extracting and processing the label as well as removing it and adding a new one. The exact method for performing a label swap depends on how the labeling was done. Chang et al. (2006) have demonstrated a labeling technique called optical carrier suppression and separation (OCSS) which uses in-band wavelength differentiation and solves issues such as RF fading that are associated with similar schemes. One way to perform a label swap in a system using OCSS is to use wavelength conversion. First, the label is separated from the payload using an optical filter. At this point the label is processed and used for routing and control. Processing can be done optically or by converting the label into the electronic domain. The next step is to convert the new label and the payload to different wavelengths using an optical modulator and a wavelength conversion method. An example of wavelength conversion is a technique that uses cross-gain modulation (XGM) or cross-phase modulation (XPM) effects present in semiconductor optical amplifiers (SOAs). The final step involves combining the new label with the wavelength shifted payload using an optical coupler. Note that the distance between the payload and the label in terms of wavelength spectrum will not have changed.

7. Optical Routing

In discussing optical labeling, one important element that has thus far been ignored is the technique used for performing the actual routing indicated by the labels, and a large part of routing is switching. Optical switching is performed by a switching fabric made of switching elements interconnected with input and output ports via a propagation medium such as optical fiber. Chang et al. (2006) suggest six qualities desirable in optical switching fabrics and analyze various attempts to design switching fabrics that optimize these qualities. The attributes are fast configurability, minimal crosstalk coupled with a high on-off extinction ratio, flexibility in changing signal transmission characteristics, scalability with regards to the number of ports, minimal power consumption, and small size. Though many different designs have been proposed, each of the fabrics demonstrated to-date has limitations. Some, such as those using MEMs, thermo-optic effect, and liquid crystals, have slow configurability. Others, such as those based on the electro-optic effect, suffer from high loses and are not easily scaled. Switching fabrics that use carrier injections to change the refractive index in semiconducting materials have fast switching times, but their other characteristics vary greatly depending on the implementation, and no viable scaled switching fabrics have been demonstrated yet. Other solutions that have been demonstrated are subject to crosstalk, inflexible signal wavelength and polarization characteristics, and high power consumption. Designing a switching fabric that overcomes these issues is an important step in implementing all-optical networks.

In addition to switching, another important part of optical routing is wavelength conversion. In addition to the uses wavelength conversion has in label swapping, it also provides a way to perform traffic merging and contention resolution - important aspects of optical routing. Chang et al. (2006) have demonstrated an implementation of OCSS with wavelength conversion for routing as well as labeling.

Experiments have shown that this OCSS scheme is capable of routing packets with 40 Gb/s payloads and 2.5 Gb/s labels. To see how this technique is used for traffic merging and contention resolution, consider a situation where a router simultaneously receives two different signals on wavelength λ_1 from two different nodes. Both have the same destination. Thus, in order to transmit them at the same time, one must be converted to wavelength λ_2. Using OCSS this can be accomplished while maintaining a fixed frequency separation between each packet's payload and label. By using a technique called four-wave mixing (FWM) to perform the wavelength conversion, the system has flexibility in bitrate and modulation format. Additionally, the label and the payload can be converted at the same time. The major disadvantages of this method are low power efficiency and order reversal of the converted payload and label in the spectral domain.

A third vital component in optical routing is optical multiplexing. Many common optical waveforms such as WDM transmit multiple signals over a single physical medium simultaneously by using different wavelength channels. To support WDM, devices for optically demultiplexing wavelength channels at a router's input and subsequently multiplexing the channels at the router's output are essential. These tasks are generally accomplished using optical filters, which have the ability to add or drop channels from the optical signal being transmitted. Numerous designs have been proposed based on diffraction gratings, dielectric thin-film filters, fiber Bragg gratings, arrayed waveguide gratings (AWG), and other technologies. However, as with several other optical networking components, methods that use photonic crystals may prove most successful, offering the best wavelength resolution. One such design proposed by Bhargava, Kumar, Kumar, Singh, and Suthar (2012) uses 1-dimensional photonic crystals built using alternating high and low refractive index materials and a defect layer. The high refractive index layers and the defect layer are made of silicon, while zinc sulfide is chosen to provide a low refractive index. The design relies on cascading the photonic crystals to separate wavelength channels. The disadvantage of this method is that power is lost as the signal passes through each photonic crystal filter. To compensate for this, an optical amplifier must be used. However, despite this drawback, the demonstrated photonic crystal based demultiplexer provides improvements in other areas, offering 0.8 nm channel spacing and the ability to tune the filters by changing the temperature of the silicon layers.

By utilizing new technologies for optical switching, wavelength conversion, and multiplexing, effective optical routers are being developed for use in packet switched networks. Researchers have even begun to successfully demonstrate such networks in laboratory experiments. For example, Kitayama, Olmos, and Tokushima (2009) have constructed a system capable of optical packet switching using an integrated and pigtailed add-drop filter based on photonic crystals. Experiments show that the system is capable of routing 10 Gb/s signals with moderate power loss. These results suggest that as incremental improvements are made, optical packet switched routing technology has the potential for use in practical telecommunications applications.

8. Optical Routing Protocols

The culmination of advances in optical labeling and optical routing is the ability to implement optical routing protocols to replace electronic domain protocols such as multiprotocol label switching (MPLS). Kitayama and Murata (2001) present two protocols that have been proposed for optical routing and fall within the generalized MPLS framework (GMPLS). The first is known as multiprotocol lambda switching (MPλS), and the other is MPLS-based optical code label switching (OC-MPLS). Both of these protocols will be described in more detail, and their advantages and disadvantages will be considered.

Since both MPλS and OC-MPLS make use of principles found in MPLS, a brief description of this protocol is provided. The basic purpose of MPLS is to provide connection-oriented routing using label switched paths (LSPs). These LSPs are set up in one direction only, and all packets in a session must follow the same path. To implement MPLS, label switched routers (LSRs) must be used. These routers perform label swapping, which is needed to determine the next LSR in the path. The first router in the

LSP is known as the ingress router, and it is responsible for attaching a label to the packet being transmitted. The last router, known as the egress router, is likewise responsible for removing the label as the packet reaches its destination. One last property of MPLS to note is that LSPs are created either using hop-by-hop IP routing or explicit routing. With this understanding of MPLS, attention can now be focused on MPLS-based optical protocols.

Kitayama and Murata (2001) describe MPλS operation within a physical network similar to what has been discussed so far. The network consists of optical nodes connected by optical fiber links with optical switching elements strategically placed to direct packets. Once again, WDM is the waveform considered for signal transmission, meaning packets are carried simultaneously over multiple wavelength channels. To implement MPλS in an optical network, MPLS ingress and egress routers are placed at the edge of the network. These LSR nodes take packets using MPLS in the electronic domain and convert them to optical packets. Optical labeling is accomplished by using the wavelength channels themselves as the labels. Consequently, the number of possible LSPs provided by the protocol is limited by wavelength channel availability. Likewise, optical label swapping within LSRs is implemented by changing the wavelength channels of the packets. Based on the premise that optical LSRs are difficult and costly to implement, MPλS seeks to minimize their use through circuit-switching. Few LSRs are used within the network besides those used at the ingress and egress points. Instead, dedicated circuits are set up to route packets across large portions of the network. Another advantage of doing this is the reduction in the needed number of wavelength channels for label swapping. However, this method sacrifices the any-to-any connectivity and flexibility provided by packet switching. Regaining this flexibility without increasing the number of wavelength channels is an important goal that necessitates additional packet processing. The task is made even more difficult by the desire to perform this processing optically rather than electronically.

According to Kitayama and Murata (2001), a primary challenge associated with MPλS is capacity granularity. Each circuit-switched connection between LSRs requires the exclusive use of a wavelength channel, which means a significant portion of the network's capacity is wasted if the bandwidth needed for a particular LSP is less than the bandwidth provided by a wavelength channel. While some potential solutions to the granularity problem have been proposed, the attempts, which have been largely based on using optical wavelength label merging and splitting, have proven difficult. Furthermore, another challenge present in MPλS is determining the best configuration of LSPs and circuit-switched connections. The difficulty lies in the physical, inflexible nature of the underlying network topology. Predicting the characteristics of the IP traffic load prior to constructing the network and monitoring it is a challenging task, and reconfiguring the network to optimize it after extended monitoring poses significant penalties for users. Some solutions have been proposed involving channel rerouting using color-interchange and virtual topology reconfiguration. However, further research is needed.

To overcome the limitations presented by MPλS, another protocol known as OC-MPLS has been proposed. Kitayama and Murata (2001) present OC-MPLS as MPLS implemented with photonic LSRs that are capable of performing optical label processing and swapping. In previous discussion of optical labeling, three methods were discussed: time-serial labeling, variable code labeling, and variable wavelength labeling. The OC-MPLS framework uses the variable code labeling method. The encoding schemes used are binary phase shift keying (BPSK) and on-off keying (OOK). In implementing OC-MPLS within an LSR, each wavelength channel is processed by a separate label swapping entity. This means the wavelength channels can all use the same set of optical codes. However, Optical Code Division Multiplexing (OCDM) is not used to encode different labels for each of the wavelength channels that make up the optical signal. Thus, all packets sent at the same time on the same WDM link must have the same label across all wavelength channels. As a result, optical buffering is essential in packet switched networks using OC-MPLS.

To better understand OC-MPLS, the labeling process must be considered in greater detail. When an optical signal is processed by an LSR, the first step is to extract the label from the packet using an appropriate optical decoding scheme as determined by the type of encoding used. Once this is accomplished, the label is optically duplicated using an optical amplifier and is power-split into several copies. One copy is created for each entry in the table of labels stored within the LSR so that the label can be correlated in parallel with all of the possible matches. The correct match is determined by comparing the correlator outputs against a threshold. A label correlated with itself is called an autocorrelation and will result in the highest output peak. Kitayama and Murata (2001) report that the process has been demonstrated using 8-symbol BPSK optical codes at a bit rate of 10 Gb/s.

The clear advantage of using the OC-MPLS protocol is the ability to gain the flexibility and superior capacity utilization of packet switching while still benefiting from the speed of all-optical routing and processing. However, according to Kitayama and Murata (2001), OC-MPLS is presented with some challenges that must be overcome. Since OC-MPLS relies on analog processing techniques for labeling, the protocol is susceptible to waveform distortions that result when signals are transmitted over long distances. Waveform distortions can be caused by issues such as chromatic dispersion and nonlinearities in optical fibers. In addition to transmission challenges, current OC-MPLS implementations also face the limitation that 8-symbol BPSK optical codes limit a channel to only 128 labels. While the issues present in current OC-MPLS schemes are serious, further research and design has the potential to overcome them. In fact, some research along these lines has already taken place. In an effort to solve the transmission problem, Kitayama and Murata (2001) report that compensation schemes have been devised allowing acceptably undistorted transmission over distances of over 50 km. As these issues are solved, OC-MPLS or a similar all-optical packet switching protocol may well find adoption in practical networking applications.

In examining the advantages and disadvantages of both MPλS and OC-MPLS, the need for further research is made apparent. Both protocols have unsolved shortcomings that must be addressed. However, while MPλS offers some significant advantages and may prove useful in future networking applications, its fundamental limitations seem to make OC-MPLS a more desirable approach. OC-MPLS represents a protocol for all-optical packet switched networking that has the potential to offer many if not all of the looked for benefits of such networks. Though, achieving this goal will depend on advances made in all of the types of networking components discussed thus far.

9. Optical Packet Scheduling

In addition to the core networking components discussed so far, a variety of other elements must be considered in transitioning to all-optical networks. One such element is optical packet switching. As has already been made clear, optical buffering is an essential part of an effective OPS network. However, at present the main method used in buffering is fiber delay lines (FDLs). These buffers are highly susceptible to packet loss due to signal loss and noise experienced by the optical components. The problem is compounded by the need to recirculate packets through the FDLs numerous times to attain the desired delay. To alleviate this issue, Chou and Lin (2011) have proposed a packet scheduling algorithm that takes into account latency and residual distance to schedule packets in a manner that reduces packet loss.

The key to the packet scheduling algorithm proposed by Chou and Lin (2011) is prioritizing packets according to the equation

$$\Pi(R, L) = \frac{L}{R^{\rho}}$$

where L is the latency of a packet measured in hops, R is the residual distance measured in hops between the packet's present location and its destination, and ρ is the relative-distance factor. A larger value for $\Pi(R, L)$ denotes a higher priority. The relative-distance factor is used to weight L and R. For example, if ρ is greater than one, R has a heavier weighting than L. Likewise, if ρ is less than one, then L has a heavier weighting than R.

In order to obtain an optimal packet prioritization, the proper value for ρ must be determined. Chou and Lin (2011) have done this using experimental and analytical processes. The results show that setting $\rho = 0$ and $\rho = -\infty$ result in reduced packet loss for light loads, but these settings also increase average delay. Conversely, setting $\rho = -\infty$ reduces packet loss during heavy network loading and can reduce average delay. These and other observations lead to a set of three rules which are used to dynamically change ρ to minimize packet loss: use negative ρ for low traffic load, increase ρ as the traffic load increases, and increase ρ as the latency limit increases. Using these rules, the proposed scheduling algorithm has been shown to reduce packet loss by 71% for light loads when compared to a least latency first (LLF) scheme. For heavy loads, the algorithm has been shown to reduce packet loss by 4% compared to LLF. Consequently, the proposed scheduling algorithm is a clear improvement over LLF that demonstrates the importance of proper packet scheduling in implementing all-optical packet switched networks.

10. Optical Network Virtualization

Another component that should be considered when designing all-optical networks is virtualization. A major challenge in networking is configuring networks for different application types with different usage patterns. A common solution to this dilemma is to use virtualization, a technique that uses abstraction and partitioning to divide one or more physical networks up into a set of virtual networks that can be assigned different bandwidth and QoS characteristics. Implementing virtualization in the optical realm presents a new set of challenges to be solved as a result of the analogue nature of optical networks. For example, if an optical network is partitioned, the virtual networks may interfere with each other, because they are sharing the same physical optical resource. Escalona, Nejabati, Peng, and Simeonidou (2011) have proposed a solution that takes these physical resource characteristics into account.

The virtualization architecture proposed by Escalona et al. (2011) contains four layers. The first is the physical layer which is composed of all the optical network components present in the network. The second layer is the physical layer control and management. This layer provides several tools and functions related to managing the physical layer. For instance it's used to advertise the physical layer's capabilities and resources to the layer above it as well as providing access to the physical layer. Additionally, this layer abstracts away the implementation details of the physical layer. The next layer is the optical virtualization layer - the most innovative part of the solution. This layer uses the controls provided by the layer below it to manage network resources, allowing it to create and monitor virtual networks. It also provides virtual resources within the virtual networks with an interface for controlling and managing the virtual networks. The virtual optical network control and management layer is the final layer. It provides the end user of a virtual network with controls for managing the network. This layer may be implemented using GMPLS.

The primary enabling technology of the virtualization architecture proposed by Escalona et al. (2011) is OOFDM. Utilizing this optical waveform, optical links can be virtualized with sufficiently precise bandwidth granularity by assigning a portion of available subcarriers to each virtual link. In doing this, the physical network can be partitioned into a set of virtual networks with their own virtual links which are largely independent of each other. By creating virtual networks in this manner, the benefits of virtualization, namely flexible bandwidth and QoS assignment for different applications, can be realized for optical networks.

11. Optical Network Security

The final optical network design element that will be considered is network security. While all-optical networks are subject to traditional attacks performed against electronic and hybrid optical-electronic networks, they are also vulnerable to additional types of attacks because of various characteristics such as data transparency, high bitrates, lack of regeneration, and susceptibility to crosstalk and cross modulation. Additionally, attacks tend to spread quickly and silently, causing significant damage before they are detected and addressed. According to Arozullah and Rahman (2013), the most vulnerable optical networking components are amplifiers, fibers, and switches, because these components are highly susceptible to gain competition and crosstalk. For example, an attacker could perform what is known as an in-band jamming attack against a WDM network by injecting a high powered signal into an optical router on a particular wavelength. Since routers use a single switching fabric to handle all traffic on a particular wavelength, the high powered jamming signal could introduce crosstalk within the router that would interfere with signals from other optical fibers. Another type of attack, called a gain competition attack, involves injecting a strong out-of-band signal into an optical amplifier. If the attack signal is within the passband of the amplifier, the device will not be able to distinguish it from a legitimate signal and will subsequently fail to properly amplify the real signals it receives.

To secure optical networks from the various types of attacks to which they might be exposed, Arozullah and Rahman (2013) propose a comprehensive security strategy involving a combination of proactive prevention and reactive restoration. The plan involves three phases, the first of which is the creation of a component security database which resides in each optical node. The database contains a record of the security status of each component in the network. If the state of a component changes, for example if it is under attack, the component exchanges messages with other nodes in the network, updating them with the new status. The second phase focuses on providing the most secure path for packets to take from source to destination. A node accomplishes this by selecting the most secure components from the previously mentioned database when determining the path for packets to use. The routing algorithm used is Open Shortest Path First (OSPF) where the link weights take both link length and link security status into account. The final phase provides the ability to partially restore network links when an attack occurs. To do this, security envelopes are placed around susceptible components through the use of additional resources to provide backups. The last step has the disadvantage of adding cost to the system, but it provides protection against data loss and prevents the network link from needing to be dismantled and replaced with a new one.

The security strategy offered by Arozullah and Rahman (2013) has been analytically modeled and evaluated through the use of simulations. The system has been shown to offer protection against common optical network attacks such as in-band and out-of-band jamming. Given the severe damage possible in terms of data loss and network failure, a comprehensive security strategy such as the one proposed by Arozullah and Rahman (2013) is an important consideration in all-optical network design.

12. Avionics Case Study

Having examined the technologies involved in providing all-optical packet switched networks, a specific use case will now be briefly considered. The use case is prompted by the strong drive in the avionics industry to increase network bandwidth while reducing size, weight, and power (SWaP) by upgrading electrical networking components with optical counterparts. To accomplish this goal, an optical router is necessary that can connect avionics modules through a common backplane. Further, this router must be configurable. Prather, Roman, Sharkawy, and Zablocki (2011) have proposed a design for such a router using a photonic crystal directional coupler and a bi-directional routing fabric. The system uses a number of the concepts discussed previously such as photonic crystal waveguides. In a method similar to one previously discussed, the crystals are constructed from silicon and other materials and can be configured by modifying the silicon's index of refraction. This allows them to act as switches, routing network packets between different avionics components. By using these advanced optical components, Prather et al. (2011) have been able to achieve the goal of greater network capacity while reducing SWaP.

13. Conclusion

This paper has presented an overview of the technological advances being made in optical networking that may eventually enable all-optical packet switched networks. A model for such networks has been presented, and the various components that constitute the model have been discussed. In addition, general overviews of optical switched networks and the waveforms they use have been provided. Further, a number of additional technologies helpful in the implementation of optical networks have been considered as well as a case study demonstrating how optical networking technologies are being applied to real world applications. The growing need for all-optical packet switched networks is clear, and the key enabling technologies are being developed. For these networks, and for their potential users, the future looks bright.

References

Arozullah, M., Rahman, F. (2013). Real Time Securing of All-Optical Networks Against Security Attacks at the Physical Level. *International Journal of Network Security & Its Applications*, 2013, 5(4), 1. ISSN:09752307

Bhargava, A., Kumar, A., Kumar, V., Singh, K., Suthar, B. (2012). Tunable Wavelength Demultiplexer for DWDM Application Using 1-D Photonic Crystal. *Progress in Electromagnetics Research Letters*, 2012, 33, 27-35. DOI:10.2528/PIERL12042009

Bhusari, V., Sahu, A. (2013). Optical Burst Switching. *International Journal of Advanced Research in Computer Science*, 2013, 4(6), 74. ISSN:09765697

Boyd, R., Narum, P. (2007). Slow- and Fast-Light: Fundamental Limitations. *Journal of Modern Optics*, 2007, 54(16-17) 2403-2411. DOI: 10.1080/09500340701639649

Chang, G.K., Chowdhury, A., Jia, Z., Yeo, Y.K., Yu, J. (2006). Enabling Technologies for Next-Generation Optical Packet-Switching Networks. P*roceedings of the IEEE*, 2006, 94(5), 892-910. DOI:10.1109/JPROC.2006.873433

Chou, K.H., Lin, W. (2011). A Latency-Aware Scheduling Algorithm for All-Optical Packet Switching Networks with FDL Buffers. *Photonic Network Communications*, 2011, 21(1), 45-55. DOI:10.1007/s11107-010-0279-6

Eisenstein, G., Korotky, S., Tucker, R. (1988). Optical Time-Division Multiplexing for Very High Bit-Rate Transmission. *Journal of Lightwave Technology*, 1988, 6(11), 1737-1749. doi:10.1109/50.9991

Escalona, E., Nejabati, R., Peng, S., Simeonidou, D. (2011). Optical Network Virtualization. *15th International Conference on Optical Network Design and Modeling*, 2011, 1-5. DOI:10.1364/ACPC.2013.AW3H.2

Giordani, S., Raymo, F. (2002). All-Optical Processing With Molecular Switches. *Proceedings of the National Academy of Sciences of the United States of America*, 2002, 99(8), 4941-4944. ISSN:00278424

Ishio, H., Minowa, J., Nosu, K. (1984). Review and Status of Wavelength-Division-Multiplexing Technology and Its Application. *Journal of Lightwave Technology*, 1984, 2(4), 448-463. doi:10.1109/JLT.1984.1073653

Kitayama, K., Murata, M. (2001). A Perspective on Photonic Multiprotocol Label Switching. *IEEE Network*, 2001, 15(4), 56-63. DOI:10.1109/65.941837

Kitayama, K., Olmos, J.J.V., Tokushima, M. (2010). Packet Switching Demonstrator Using an Integrated and Pigtailed Add-Drop Filter Based on Photonic Crystal Structures. *IEEE Journal of Selected Topics in Quantum Electronics*, 2010, 16(1), 332-337. DOI:10.1109/JSTQE.2009.2028901

Kuramochi, E., Mitsugi, S., Notomi, M., Shinya, A., Tanabe, T. (2005). Fast Bistable All-Optical Switch and Memory on a Silicon Photonic Crystal On-Chip. *Optics Letters*, 2005, 30(19), 2575-2577. doi:10.1364/OL.30.002575

Namiki, S., Shioda, S. (2010). Fundamental Studies on Ultra-High-Speed Optical LAN Using Optical Circuit Switching. *Photonic Network Communications*, 2010, 19(1), 32-41. doi:10.1007/s11107-009-0208-8

Pellicer, P., Redondo, A., Zaballa, J. (2009). Enabling Technologies for Future All-Optical Packet Switched Networks. *International Conference on Ultra Modern Telecommunications & Workshops*, 2009, IEEE, 1-6. doi:10.1109/ICUMT.2009.5345461

Prather, D., Roman, M., Sharkawy, A., Zablocki, M. (2011). Chip-Scale Photonic Routing Fabrics for Avionic and Satellite Applications. *Avionics, Fiber-Optics and Photonics Technology Conference,* 2011, IEEE, 75-76. DOI:10.1109/AVFOP.2011.6082134