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Evaluating Efficiency of Multi-Layered Switch Architecture in All-Optical Networks

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Abstract
This paper describes the switch architecture and its individual components and evaluates its performance. The growth of internet increases the range of future services that demand more network capacity and higher data rates. Network and system concepts are evolving accordingly using fiber-optic networks with transmission speeds more than 40 Gb/s as the base environment. Therefore, the creation of completely optical networks corresponding equipment is required. One of the basic elements of such network is a switchboard. We propose and analyze layered switch architectures that possess high design flexibility, greatly reduced switch size, and high expandability. The paper proposes a new approach to the construction of switchboards, where the problem of servicing the competitive calls is solved. The basic principle of proposed switchboard construction is the application of multilayered matrix. This architecture is scalable, high-speed, simple, practical, and low-cost, exploiting the workhorses of today's optical communications systems: arrayed waveguide gratings, distributed feedback lasers, $LiNbO_3$ switches, and low-speed photodiodes. We performed extensive experiments and found that the optimal number of layers which is required to achieve good results is six layers. The results of using the proposed architecture is improving the efficiency of operation and reducing delay time.

Keywords: Computer Networks, $LiNbO_3$ Switches, Optical Switching, Wavelength Conversion.

INTRODUCTION

Network bandwidth is growing significantly at approximately 40% per year mainly driven by mobile and cloud technologies. As a result there is an increasing requirement from optical transport networks for additional capacity, higher spectral efficiency and lower cost per bit. Prior studies have indicated that in 2017, 90% of the client services would be 10G or below, while the network line rate has reached 100G and beyond [Roy et al., 2013] [Tarapiah et al., 2016].

All Optical Networks (AONs) are widely regarded as the ultimate solution to the communication bandwidth needs of future generations of communication networks.

Several fundamental studies focused on AONs and highlighted that the important property of AONs is the ability of wave routing, inherent only to this class of optical networks [Ramaswami et al., 2009] [Roy et al., 2013]. AONs are considered to be "transparent" to data format, data wavelength and data protocol. Since the switching is "transparent" to the data packet, the network is called all-optical network, for effective functioning of networks based on AONs required optical switches [Walrand and Varaiya, 2000]. One major benefit of using wavelength switching to create optical virtual connections is the possible reduction in equipment costs. Since we do not have to convert this wavelength into electrical form at any intermediate network node, we can reduce the number of receivers and transmitters at these nodes. Removing unnecessary components would allow us either to build a cheaper network with the same throughput, or to increase the capacity for same total cost.

One of the most perspective directions in the development of fiber-optic networks of future, potentially providing maximum complete bandwidth of optical computer networks (CN). Main characteristic feature of such networks is the absence of limitations due to electron-photon conversions that enables to increase considerably data transfer rate and their service headings. All-optical wavelength routing network are designed to provide simultaneous high bandwidth multi-user access to network resources without using of intermediate electro-optical and optoelectronic data conversions which contribution to response time decrease and accordingly to reduction of CN throughput.

Among the categories of all-optical networks [Buckman et al., 1995] [Dzanko et al., 2014], the class of transparent AONs is best suited to satisfying the needs of a large network or internetwork. These networks perform no optical-to-electrical conversion of the optical payload within the network, thus preserving transparency. Large all-optical internetworks can be formed by interconnecting multiple all-optical networks. They also lend themselves to hierarchical control and management, an important requirement for the commercial deployment of these networks [Varma and Raghavendra, 1993]. Therefore, our switchboard design focuses on providing wavelength transparency for data paths, still allowing dynamic reconfiguration.

However, wavelength switching faces challenges that are: routing or data piping from input port to output port, and disambiguation (or conflicts solution); in case of several packets arrive simultaneously on the same output port. The main contribution of this research is overcoming the aforementioned challenges by proposing the multilayer switching architecture that is able to process competitive packets. The first challenge is solved by conventional methods and by means of switchboard architecture. The latter challenge is solved, as a rule, by means of buffering circuits; it is determined by the features of switchboard architecture. After extensive experiments, we found that the optimal number of layers which is required to achieve good results is six layers. The results of using the proposed architecture is improving the efficiency of operation and reducing delay time.

In this paper, we describe a Wavelength Division Multiplexing (WDM) that provides wavelength-transparent data paths between end points. The network is based on a new scheme for switching architecture in AONs using a multilayered switchboard. This paper describes the switch architecture and its individual components, evaluates its performance and evaluation of switch loading dependence on the number of auxiliary layers of multilayered switching architecture has been performed.

OPTICAL SWITCHING

A switch can be abstracted as a device that takes a set of N signal inputs and is able to reproduce them in any permuted order at the output. It is characterized by different parameters such as size, switching time and energy, crosstalk, power dissipation and loss.

Switching Function

In terms of switching function, switches are divided into two types: blocking and nonblocking. A switch is said to be nonblocking if it is capable of realizing every interconnection pattern between the inputs and the outputs. If not, the switch is named as blocking. Nonblocking switches are also divided into two groups: A wide-sense nonblocking switch can connect any unused input to any unused output without rerouting any existing connection. But a strict sense (or strictly) nonblocking switch can connect regardless of the connection rule and algorithm. Also there is a broader class of nonblocking switches called rearrangeably nonblocking switches where rerouting of connections could be done. The basic switch architecture is the N x N crossbar switch. It is also called as a space switch because it separates the signals in space [Walrand and Varaiya, 2000].

The crosspoint count of a switch is often used as a measure of its complexity Figure 1 Therefore it is desirable to reduce the number of crosspoints (N^2 for N x N). This is usually done by building larger switches from stages of smaller crossbar switches. Architectures also vary according to configurations done by the 2 x 2 switches, such as Benes, Spanke, Slepian or Clos but mostly crossbar [Okayama et al., 2000] [Ramaswami et al., 2009].

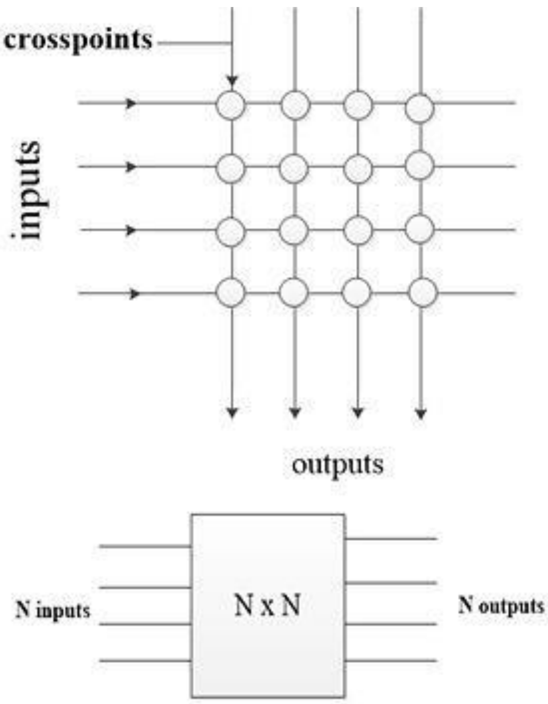

Figure 1: *N* x *N* Crossbar switch concept.

A crossbar is the ideal and most general form of a switching network, however, are difficult to scale beyond a small number of ports owing to a number of technological and architectural limitations [Varma and Raghavendra, 1993]. Hence, a multistage architecture, consisting of smaller crossbars organized in stages, must be used to attain scalability. In addition, central control of the switching network becomes impractical beyond a certain size; in large networks, it is important to provide the ability to “self-route” data through the network in a distributed fashion using information present in the optical signal itself. Our multistage switch architecture allows such self-routing capability.

Optical switching can be done by the use of one of these architectures but notice that the technology also differs. Optical modulators can be used in different types of technologies and switches are called optomechanical, electrooptic, acoustooptic, magnetooptic, thermooptic or all-optical switches [Okayama et al., 2000] [Ramaswami et al., 2009] .

Wavelength Division Multiplexing

There is also an important switching architecture used in Wavelength Division Multiplexing (WDM) systems. This switch is known as Optical Cross Connect (OXC) and sometimes called as frequency or wavelength-selective switch. It is composed of multiplexers, demultiplexers and space switch as shown in Figure 2 [Walrand and Varaiya, 2000]. Each of the N input carries n WDM channels. After demultiplexing, the nN channels are switched through a nN x nN space-division switch. Switch permutes all the channels and then they are multiplexed into N output.

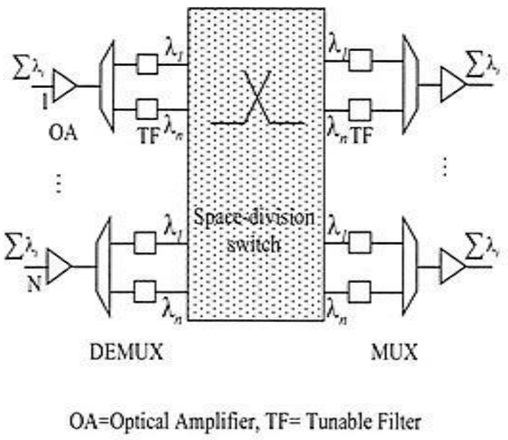

Figure 2: Architecture of an optical cross connect.

The developments of the fiber optic system initiated wide-ranging research for optical communication systems. The researchers made innovations in the lasers and in the optoelectronic components as mentioned before. But the increasing demand for bandwidth implies that the capacity of transmission must be increased. In addition, there are two fundamental ways of increasing the capacity: Time Division Multiplexing (TDM) and Frequency Division Multiplexing (FDM) [Buckman et al., 1995].

In the optical domain both are used with optical, means as optical TDM or OTDM and optical FDM or OFDM. One promising method of identifying virtual connections comes through the growing use of Wavelength Division Multiplexing (WDM) over single mode optical fiber as a transmission method. Independent streams of data are modulated using different frequencies and sent through the same piece of fiber. At the receiver, several parallel frequency sensitive filters can be used to separate the signals from each other. Wavelength division multiplexing (WDM) is an emerging technology for increasing the bandwidth of optical networks [Bennett et al., 2010] [Dzanko et al., 2014].

In multilayer WDM networks, traffic is carried over optical fiber connections which occupy a wavelength in each traversed fiber and terminates at an optical-to electrical receiver at the destination node [Bennett et al., 2010] [Dzanko et al., 2014]. The connections are optically switched at the intermediate nodes and routing and wavelength assignment mechanisms are drawn on for determining the sequence of optical fibers traversed. But there is also another types of multiplexing in light wave communications depending on the color (wavelength) of the carrier but different in detection (direct/heterodyne) and separation (optically before/electronically after photo detection) [Roy et al., 2013] [Pang et al., 2014], that is, Dense Wavelength Division Multiplexing (DWDM) is used for the same technique, but when the gaps between adjacent wavelengths are smaller.

To cope up with the increasing high capacity demands, next generation DWDM systems would require line rates greater than 100 Gb/s. Super-channels are the next-generation technology to increase spectral efficiency and maximize fiber capacity [Pang et al., 2014]. This will be complimented by the introduction of flexible grid WDM channel plan, to the existing CDC (colorless, directionless and contentionless) architecture of the multi-degree reconfigurable optical add drop multiplexer (ROADM) to become the fundamental building blocks of the next generation DWDM photonic layer [Dzanko et al., 2014].

Wavelength Routing Networks

Wavelength routing networks can be classified either static or reconfigurable depending the elements they contain. If a network does not have any switches on dynamic wavelength converters (described below), it is a static network. Otherwise, it is called reconfigurable or dynamic because of the capability of the network to change routes at nodes [Atalla et al., 2016] [Pang et al., 2014].

A wavelength converter is an optical device that converts data from one incoming wavelength to another outgoing wavelength. Without wavelength conversion an incoming signal can be optically switched to any output port but only on one wavelength. With wavelength conversion this signal could be optically switched to any output port on any wavelength [Dzanko et al., 2014]. Therefore, different physical links can be established where bit rates, protocols become insensitive, thus transparency is provided.

Figure 3 shows different types of wavelength conversion [Walrand and Varaiya, 2000]. If each wavelength is converted only to itself, then there is no conversion. If each input wavelength is converted to exactly one wavelength, fixed conversion is done. But if each input wavelength can be converted to a specific set of wavelengths, at least one less from all, conversion is named as limited while full conversion implies all possible connections are established.

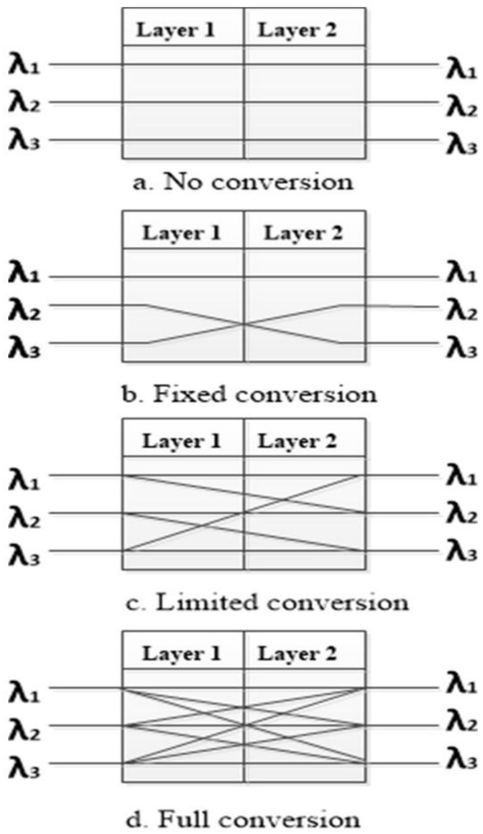

Figure 3: Wavelength conversion types.

EVALUATION OF THE SWITCH AS MULTILAYER ARCHITECTURE

One major benefit of using wavelength switching to create optical virtual connections is the possible reduction in equipment costs. Since we have no need to convert this wavelength into electrical form at any intermediate network node, we can reduce the number of receivers and transmitters at these nodes. Removing unnecessary components would allow us either to build a cheaper network with the same throughput, or to increase the capacity for the same total cost.

For creation of completely optical networks corresponding equipment is required. One of the basic elements of such network is a switchboard. Switchboard perform a wide range of functions. Let us concentrate the attention on two main functions: routing or data piping from input port to output port, and disambiguation (or conflicts solution); in case when several simultaneously arrived packets compete one and the same output port. The first function is solved by conventional methods and by means of switchboard architecture. The latter function is solved, as a rule, by means of buffering circuits; it is determined by the features of switchboard architecture.

We used the following guidelines in our design of the switchboard architecture:

- The payload must remain in optical form during its passage through the switch cells, that is no optical-electrical-optical conversion is allowed. This provides complete data-format and wavelength transparency of the signals. However, we do allow for mechanisms to sense the header information from each optical packet, from which the signals for the low-speed electronic control of the path of the optical payload are derived.
- The control function must be distributed within the switch fabric in order to avoid the bottleneck due to a central controller.
- The switchboard architecture must be scalable and modular.

Switch Architecture Design

In accordance with basic principle of operation investigated network, data packet is preceded by optical header, that consists of a set of address slots, and sequences of lengths of wavelengths, for coding of packet destination address in optical network models of devices, methods of operation organization, connection, technology etc., are studied and developed. Switch can be built on the basis of integrated fiber optic technology.

But in this case, the implementation of the device is possible, where the signal is split into multiple channels, and passes only through that channel which conducts a package in the point of setting. If it is necessary, the amplification or regeneration is carried out. In any case, the switch consists of similar cells and additional, input and output logics to performs amplification, compensation dispersion etc.

Let us consider the general device and functioning of base element of investigated network, as shows in Figure 4:

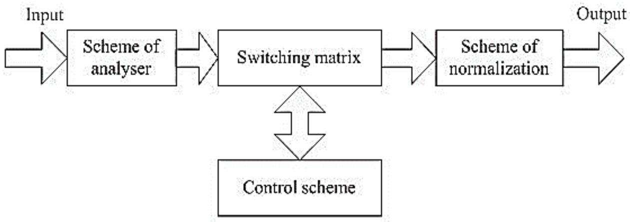

Figure 4: Structural scheme of switch.

It should be noted that rate of header slots transmission can be much below, than data transmission rate in the packet, allowing to detect and process the header with the help of relatively slow optics and electronics.

Optical address header is used for establishing the route across switching environment as it takes place in conventional packet network. Coding scheme, using numerous wavelengths is convenient for application in multistage self-routing network, where each switching node reads part of route label, establishes and transmits packet for further processing. In the given case, the number of stages in the network is equal to the number of slots in optical packet of the header - $\boldsymbol{m}$.

Operation of switching node can be presented in the following way: switching node in point $\boldsymbol{i}$ of the network uses a wavelength in the slot $\boldsymbol{i}$ of packet, to perform maximal routing, setting of route to needed output port of switching node. To avoid a necessity to perform identification of certain slots in the header, each node deletes the slot from header before the transmission of optical package on a next stage. It is achieved by means of launching of optical switch on the edge of the signal of the corresponding wavelength.

For further research it should be taken into account that whatever architectural approach is chosen for switchboard design, buffering is required everywhere. Three basic approaches regarding buffers arrangement must be considered:

- Buffering on an input: Accordance to this circuit, each switchboard input port is equipped with the buffer. More often it is used in non-blocking architecture with spatial division. Input buffering helps to solve the conflict, at which some stations simultaneously (in the beginning of transmission) try to send packets on the same target port. The packet from the buffer that goes is to port of destination only, when it becomes free.
- Buffering on an output: This type of buffering provides the buffer organization at output ports. Usually, the given circuit is applied to switchboard with full-connected topology and with the divided transfer environment. For the solution of the problem of simultaneous delivery of packets at one port, the pool of buffers as a rule is used, in an ideal case their quantity for each output port should coincide with the number of input ports.
- Buffering inside switching field: In the switchboard with spatial division buffers can be placed directly inside switching elements. But such buffering results in blocking of the first in turn, especially in case of small buffers or multi-element networks, internal buffers enter unpredictable delay while transmitting packets transfer along a route. Totally it can considerably decrease the productivity of such devices.

Multi-layer Switching Architectures

In order to construct the switchboard that are able to process the competitive packets, the multilayered switchboard are used as in Figure 5 Such switchboard improves the efficiency of operation, reduce delay time and decrease their loading.

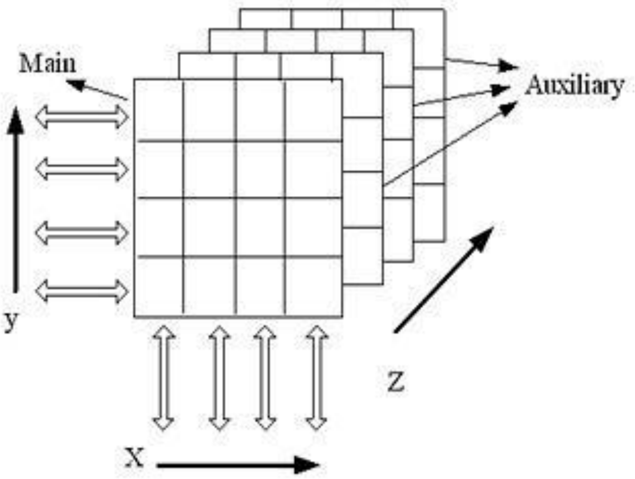

Figure 5: Multi-layered architecture of switching matrix.

But in order to apply multilayered switchboard, it is necessary to evaluate the characteristics of its functioning, namely the probability that at certain period of its operation the switchboard will be free or the probability of the freeway in the switchboard for connection of present points **[**Daadoo, M. & Daraghmi, Y., 2015**].**

Let the probability of free route from input cell (x_0, y_0, z_0) to output cell (x_n, y_n, z_n) be **[**Daadoo, M. & Daraghmi, Y., 2015**]**:

$$P(A) = P\left(\dots \begin{matrix}(x_0, y_0, z_0):(x_1, y_1, z_1);(x_1, y_1, z_1):(x_2, y_2, z_2);\dots \\ (x_{n-1}, y_{n-1}, z_{n-1}):(x_n, y_n, z_n).\end{matrix}\right) \qquad (1)$$

where n – a number of transfers.

The task is to create a matrix $S(x, y)$ and arrays $L(x, y, z)$ where states of cells are preset, Figure 6.

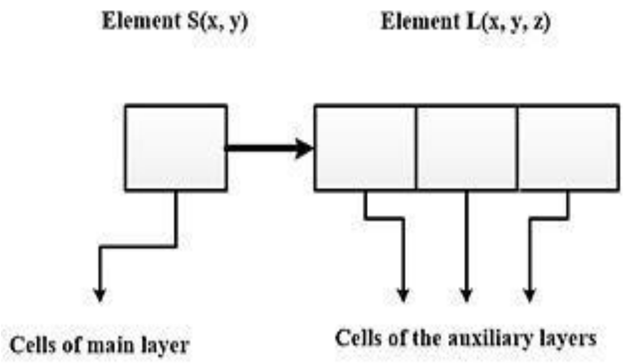

Figure 6: State of occupancy of switch cells.

Then the engaged condition is a certain surface below. This surface is conventionally free.

The probability that the route will be free is calculated in the following way:

$$P(\omega) = 1 - P(S_1) \cdot P(S_2) \cdot P(L_1) \cdot P(L_2) \cdot P(T) \qquad (2)$$

Where $P(S_1) = P(S_2) = \frac{n \times m}{\text{quantity of engaged}}$ - Probability that selected cell from the main matrix will be engaged ($(n \times m)$-size of the basic matrix);

$P(L_1) = P(L_2) = \frac{1}{\text{quantity of engaged}}$- The probability that the selected cell from the line will be engaged (l – length of the line);

$P(T)$ - Probability that the route-making program would find a freeway from the cell (x_1, y_1, z_1) to the cell $(x_{n-1}, y_{n-1}, z_{n-1})$.

Format of the Packet and Switchboard Load Factor

Headers in packet, followed by data packet which is a series of ***p*** bits, where T_h, T_d and T_r – pulse width of the header, data and reset pulses, and T_{hp}, T_{DP} and T_{RP} – width of protective interval of heading, data and reset pulses correspondingly Figure 7.

Header and payload use one and the same set of wavelengths. If the number of wavelengths is ***K***, then each bit of the header is represented by one on one of the wavelengths, meanwhile, there is no signal on the rest of ***k-1*** channels. Thus, the complete number of various configurations of heading (maximal number of nodes of the network) is K^p. Switching in such networks is performed using $LiNbO_3$-based switches. $LiNbO_3$ (lithium niobate) and Semiconductor Optical Amplifier (SOA) gate switches are most promising because of their switching speed in a range of several nanoseconds. They have also low crosstalk and low power loss, especially the integrated ones. This influences the operation frequency with which header of packet is processed with - 100 MHz, though the payload of the packet passes across the switch as across the transparent medium [Agrawal, 1992] [Buckman et al., 1996].

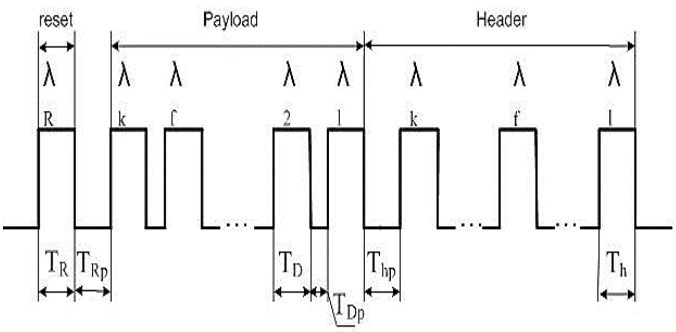

Figure 7: Format of the packet.

After payload of the packet passes the signal "Reset" follows on specially assigned wavelength λ_p, this signal returns the switch of the network into initial state. Self-routing is performed by each stage. Though theoretically such architecture provides complete transparency, nevertheless, the limitation due to peculiarities of the components, used in optical network, must be taken into consideration, before the complete transparency has been achieved.

If we assume that receiving and processing factor take normal value (λ=0,4 and μ=0,5), and the number of switchboard ports equals $m \times n$ and they are within the limits of 16 – 128 **[**Daadoo, M. & Daraghmi, Y., 2015**],** then switchboard load factor will be determined by expression Figure 8.

$$\rho = \frac{\lambda}{\mu} \times \frac{1}{\ln(n \times m)} \tag{3}$$

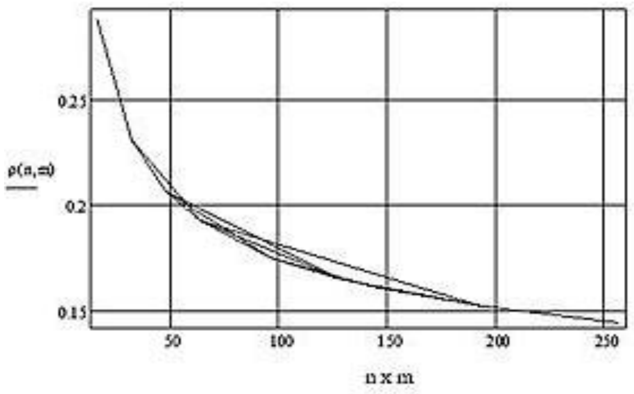

Figure 8: Dependence of switchboard load factor on the sizes of the switchboard m×n.

Switching of the Packets and Transfer Load

Switching structure N x N for switchboard, can be implemented, using $\mathbf{p=log_k(N)}$ stages (one stage per digit the header), each stage containing N/K switching elements. It differs from typical BANYAN Networks [Varma and Raghavendra, 1993], which are constructed using 2 x 2 switching elements. To avoid competition the sorting network (BATCHER type) can be installed before switching network [Varma and Raghavendra, 1993].

The switching in switchboard is performed in the following manner Figure 9.

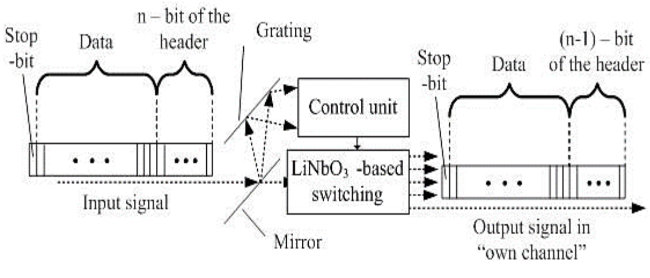

Figure 9: Switching of the packets in switchboard.

The division of optical power occurs on the mirror in proportion 10% to diffraction grating and 90% to switches. The first digit of heading with the wavelength of $\boldsymbol{\lambda_i}$, contacting the grating deflects to corresponding photo-receiver of control unit. At the edge of this pulse of light the corresponding signals of electric drive are generated, these signals switch $LiNbO_3$-based electro-optic switch on $\mathbf{i^{th}}$ output port corresponding to the wavelength header digit. Electro-optical switch remains in the turn on fixed state to the edge of reset pulse $\boldsymbol{\lambda_R}$. That is why, the whole payload $\boldsymbol{\lambda_i}$, will be transmitted across the switch on corresponding output port: packet digits, including $\boldsymbol{\lambda_R}$. Hence, switching node is transparent to any format of data, wavelength (within the limits of the band used) and transmission rate. Electro-optical switch is fabricated from $LiNbO_3$ and operates in the range of 850±5 nm. Turn on time is about 10 ns, the RF half-wave voltage is 1,55 V. The switch is polarization-dependent and is pigtailed with polarization-maintaining fiber on the input and all four outputs. There is a guard time between the falling edge of the last header pulse and the beginning of the data to allow for the turn-on time of the photodiode, electronics and $LiNbO_3$ switch and for fiber dispersion effect. The drawbacks of the given version are the followings, the necessity to use fibers with polarization characteristics, considerable losses during, back of a single integration technology of fabrication of all the elements.

During the operation of the switchboard the situations will occur; when some cells of basic layer will be engaged. Then, the transfer load will be carried out by auxiliary cells. In this case, the following expression will be valid:

$$\rho b = \frac{\rho}{k} \tag{4}$$

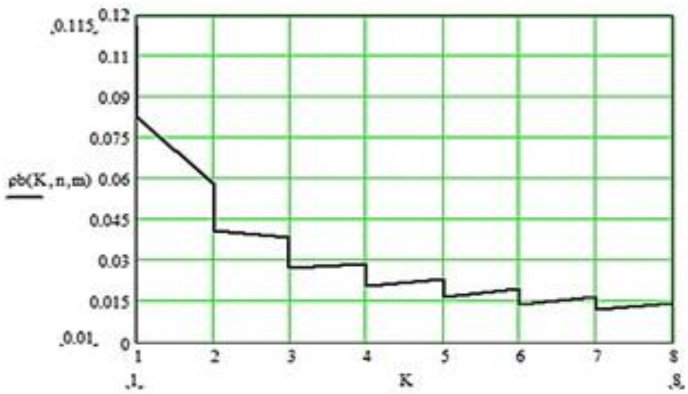

Figure 10: Dependence of switchboard load on quantity of auxiliary layers (K=8).

DIRECTIONS FOR FUTURE RESEARCH

The payload must remain in optical form during its passage through the switch cells, that is no optical- electrical-optical conversion is allowed. This provides complete data-format and wavelength transparency of the signals. However, we do allow for mechanisms to sense the header information from each optical packet, from which the signals for the low-speed electronic control of the path of the optical payload are derived.

Among the various multistage network architectures [Dzanko et al., 2014] [Roy et al., 2013] , we chose the class of self-routing switching fabrics, i.e. fabrics that switch incoming signals to the proper destination based on a "routing tag" attached to the payload and is sensed at each switching elements. However, instead of encoding the routing tag as a sequence of bits in a single wavelength channel, we are currently demonstrating the feasibility of routing based on the wavelength-encoded header by constructing a small prototype switchboard. The demonstration of multistage switch fabric is planned for later this year.

CONCLUSION

On the basis of the suggested material, it can be determined that 6 – layer architecture will be optimal, as it is seen from the graphic Figure 10 the unloading gain of the switchboard considerably decreases. As a matter of fact, for each of switchboard type separate calculations must be carried out and the given version is intended for completely optical switchboard based on 16 – nonblocking ports for 10/100/1000 Ethernet.

While designing competitive switchboard, we should provide such services as the possibility of authorization, performance, number of ports, encryption, data compression, class of service (CoS) and quality of service (QoS), gateway screens, delivery of the detailed information both by the separate user, and by their streams, scalability, security, the opportunity to install additional modules, low price, high degree of readiness, reserve copying and restoration, fault – proof.

For further research it should be taken into account that whatever architectural approach is chosen for switchboard design, buffering is required everywhere. Three basic approaches regarding buffers arrangement must be considered Buffering on input, Buffering on output and Buffering inside switching field.

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REFERENCES

[1] Atalla, S., Tarapiah, S., El Hendy, M., & Hashim, K. F. B. (2016). Smart Algorithms for Hierarchical Clustering in Optical Network. International Journal of Communication Networks and Information Security (IJCNIS), 8(2).

[2] Agrawal, G. P. (1992). Fiber-Optic Communication Systems, A John Wiley & Sons. Inc., Publication.

[3] Bennett, G., Ahuja, S., Hand, S. J., Liou, C., Vusirikala, V., &Melle, S. (2010, May). Analysis of Network Bandwidth Efficiency for Next-Generation 100Gb/s WDM Architectures. In Proc. TERENA Networking Conference.

[4] Buckman, L. A., Wu, M. S., Giaretta, G., Li, G. S., Pepeljugoski, P., Jeong, G., ...& Chang-Hasnain, C. J. (1995, February). Demonstration of a Novel All-Optical Switching Node in a Self-Routed Wavelength-Addressable Network (SWANET),". In Proceedings of Optical Fiber Conference.

[5] Buckman, L. A. (1996). Applications in optical communications: optical transmission of millimeter-wave signals; and, an all-optical wavelength-routed switching network. University of California, Berkeley.

[6] Daadoo, M., & Daraghmi, Y. (2015, August). Searching of optimum characteristics of multi-layer switching architecture in all-optical networks. InHeterogeneous Networking for Quality, Reliability, Security and Robustness (QSHINE), 2015 11th International Conference on (pp. 50-55). IEEE.

[7] Džanko, M., Furdek, M., Zervas, G., &Simeonidou, D. (2014). Evaluating availability of optical networks based on self-healing network function programmable ROADMs. Journal of Optical Communications and Networking, 6(11), 974-987.

[8] Okayama, H., Okabe, Y., Arai, T., Kamijoh, T., &Tsuruoka, T. (2000). Two-module stage optical switch network. Journal of lightwave technology, 18(4), 469.

[9] Pang, X., Beltrán, M., Sánchez, J., Pellicer, E., Olmos, J. V., Llorente, R., &Monroy, I. T. (2014). Centralized optical-frequency-comb-based RF carrier generator for DWDM fiber-wireless access systems. Journal of Optical Communications and Networking, 6(1), 1-7.

[10] Ramaswami, R., Sivarajan, K., & Sasaki, G. (2009). Optical networks: a practical perspective. Morgan Kaufmann.

[11] Roy, S., Malik, A., Deore, A., Ahuja, S., Turkcu, O., Hand, S., &Melle, S. (2013, March). Evaluating efficiency of multi-layer switching in future optical transport networks. In National Fiber Optic Engineers Conference (pp. NTh4J-2). Optical Society of America.

[12] Tarapiah, S., Atalla, S., Hashim, K. F. B., & Daadoo, M. (2016). Mobile Network Planing Process Case Study-3G Network. Computer and Information Science, 9(3), 115.

[13] Varma, A., & Raghavendra, C. S. (1993).Interconnection networks for multiprocessors and multicomputers: theory and practice. IEEE Computer Society Press.

[14] Walrand, J., & Varaiya, P. P. (2000). High-performance communication networks. Morgan Kaufmann